JPL-TECHNICAL MEMORANDUM-33-335

JET PROPULSION LABORATORY WIND TUNNEL FACILITIES

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

April 1, 1967

TECHNICAL MEMORANDUM 33-335

Prepared Under Contract No. NAS 7-100
National Aeronautics & Space Administration

Preface

The Jet Propulsion Laboratory, located in Pasadena, California, is operated for the National Aeronautics and Space Administration by the California Institute of Technology. This Technical Memorandum supersedes JPL Technical Release 34-257 in describing the wind tunnel facilities that exist at the Laboratory.

The purpose of this memorandum is to provide a source of technical and operating information relative to these wind tunnels, and it is intended that it be used in performing the general planning necessary to conduct aerodynamic tests. Much of the basic information contained herein was obtained by members of the staff of the Aerodynamic Facilities Section over a period of years, but since its last publication, the facilities have been improved and upgraded. Mr. J. Gilbert Herrera, Supervisor of the Wind Tunnel Operations Group, has revised and updated the available information for the JPL wind tunnels and has edited this memorandum.

E. A. Laumann, *Manager*
Aerodynamic Facilities Section

Contents

PRECEDING PAGE BLANK NOT FILMED.

General Description of the Wind Tunnels

The present wind tunnel facilities at the Jet Propulsion Laboratory include a 20-inch supersonic wind tunnel (SWT) and a 21-inch hypersonic wind tunnel (HWT). Both wind tunnels are of the continuous-flow, variable-density type, and each utilizes a two-dimensional flexible nozzle* which can provide an infinite choice of test section Mach numbers within a specified range. A total of twelve compressors are available to supply air to both wind tunnels: eleven are centrifugal, and one is of the axial-flow type. A dryer used to extract moisture from the air before it enters the tunnels is composed of a refrigerator which removes 90% of the moisture, and activated alumina beds that extract much of the remaining 10%.

The Mach-number range of the supersonic wind tunnel varies from 1.3 to 5.0 (although runs to $M = 5.6$ have been made), with corresponding earth pressure-altitude simulation from 15,000 to 180,000 feet. Its geometric test section is 18 inches wide and a nominal 20 inches high. The hypersonic wind tunnel can be operated in a Mach-number range which varies from 4.0 to 11.0 and will simulate an earth pressure altitude from 85,000 to 220,000 feet. With the aid of a permanently installed electric heater, it is possible to vary the supply air temperature from 100 to 1350°F. The wind tunnel test section is 21 inches wide at the downstream end and 15 to 28 inches high (adjustable). The side walls each diverge approximately 0.5 deg to compensate for boundary-layer thickness. Several views of each tunnel are shown in Figs. 1 and 2.

*It should be noted that the 21-inch HWT utilizes a pair of solid throat blocks (with adjustable throat height) which remain dimensionally stable for all practical purposes in spite of the heated high-pressure supply air. The philosophy behind the design of the 21-inch HWT is described in Ref. 1.

Required Test Information

In order to properly prepare a test program to be conducted in the wind tunnel facilities, it is important that the Aerodynamic Facilities Section be in possession of all pertinent information well in advance of the scheduled test date. To ensure this, several steps must be taken before the testing can begin.

Test Proposal

Two copies of a test proposal describing the contemplated wind tunnel program should be submitted to the Manager, Aerodynamic Facilities Section, at least 5 months prior to the anticipated test. This proposal should include, but not necessarily be restricted to, the following items: (1) the sponsoring agency; (2) the purpose, technical objectives, and justifications of the test; (3) the wind tunnel test conditions; (4) the model description and proposed model suspension equipment; (5) required auxiliary equipment and instrumentation; (6) necessary raw and reduced data; and (7) a description of potential problem areas or questions which need resolution.

Advanced Planning Conference

After the Section Manager reviews the proposal and decides that the test program and the JPL facilities are compatible, the cognizant engineer of the establishment requesting the use of the wind tunnel is invited to participate in an advanced planning conference. In this conference, held at least 4 months prior to the test, the test proposal is reviewed and discussed. If the cognizant engineer and the staff of the Aerodynamic Facilities Section agree that the test program can and should be conducted in the facilities, the necessary test authorization is sought, and a model design conference is scheduled.

Model Design Conference

The model or equipment design conference is held approximately 3 months before the scheduled test. At this time, two copies of preliminary drawings, stress reports, anticipated loads, etc., should be made available to the Aerodynamic Facilities Section staff for review and evaluation.

Pre-Test Conference

A pre-test conference is held about 2 weeks prior to the test. Two copies of the pre-test report, containing the following information, are required:

1. Statement indicating purpose of test.
2. Run schedule (range and increments of variable parameter, photographic requirements, priority notation).
3. Model configuration notation (symbol definitions, surface deflection notation, special nomenclature).
4. Instrumentation description (pressure orifice location and identification, thermocouple location and identification, balance description, description of special instruments).
5. Description of special test techniques.

6. Estimate of maximum aerodynamic forces and moments about the applicable balance reference point, and estimate of variations within these maxima due to model surface deflections and/or configuration changes.
7. Model and model-installation assembly drawings.
8. Stress reports.
9. Post-test disposition instructions for all test-unique material.
10. List of employees expected to visit JPL in connection with the test so that clearances, if required, may be verified and authorization for badges may be established at the gate.

Additional Requirements

After all of the preliminary test information and requirements have been exchanged between the Aerodynamic Facilities Section staff and the cognizant engineer, and no less than 1 week prior to the test, the following information and materials must be supplied:

1. Results of model deflection and internal balance calibrations performed prior to shipping model (two copies).
2. Inspection report or equivalent for verification of model dimensions, alignment, and settings of model surfaces (two copies).
3. All model parts, photographic equipment, and associated test instrumentation (shipped with proper vouchers).

The cognizant engineer, model mechanic, and electronic technician (if applicable) should be available to work with the Aerodynamic Facilities Section personnel during pre-test preparation and model installation.

JPL Services

JPL provides a variety of services for tests that are run in the wind tunnels to ensure efficient use of the tunnels and proper conduct of the programs. After the preliminary planning has taken place and a test has been scheduled, a JPL project engineer is assigned to the test. His duties include (1) coordinating the work performed by JPL with that of the person or testing establishment for which the test is being run, (2) collecting test data, (3) reducing test data, and (4) writing a test report which describes the model, the test conditions, and the validity of the data. (Normally, the report will present the data, but will not attempt to analyze the results nor draw conclusions.) The project engineer has at his disposal the services of a test preparation group and the JPL photography laboratory. In addition, he may call upon machine shop and instrumentation facilities in the wind tunnel area to perform minor supplementary model and instrumentation work.

In order for JPL to conduct a wind tunnel test which requires a material expenditure beyond that normally budgeted, it is necessary to charge the testing establishment for this special expense. The occasional special costs are determined by JPL and discussed with the cognizant engineer from the testing establishment prior to the pre-test conference. The latter then submits a letter to the Section Manager requesting that JPL furnish the extra cost material and specifies the quantity of material needed, including a purchase order number against which JPL may charge the material.

Maximum Model Size Determination

The portion of the test section that can be used for reliable aerodynamic testing is a function of the model geometry, tunnel Mach number, and Reynolds number. The model sizing information which follows has been partially verified experimentally in the 20-inch SWT (Ref. 2).

The maximum permissible model frontal area that will permit establishment of flow in the test section is larger than the maximum area which will allow the formation of a proper model wake. The comparison of these two areas for spheres is shown in Fig. 3. As a typical means of converting these areas to models of different shapes, such as cones, a relationship is presented in Fig. 4. In general, as the drag coefficient of a model is decreased, the frontal area may be increased without disrupting the flow or proper wake-formation criteria.

Once the model frontal area has been decided upon, it is possible to determine the maximum model length. To guide the cognizant engineer in estimating the permissible model length, various pertinent dimensional quantities for the test section are presented in Table 1. A typical requirement for a test in which the model is to be pitched and/or yawed is that the model not enter the tunnel boundary layer. The test core size determined from pitot pressure profiles is $(h_g - 2\delta) \times (w_g - 2\delta)$ (see Table 1). This relationship indicates a core that is approximately 16 inches wide by 18 inches high in the SWT at a Mach number of 2, and a core that is approximately 10 inches wide by 14 inches high in the HWT at a Mach number of 10.1. It must be noted in the case of the HWT that although the total temperature (T_0) core is approximately equal to the pitot pressure (P_0') core at the lower Mach numbers, at 10.1, it is considerably less than the pitot pressure core. (Representative pitot pressure and total temperature profiles are shown in Figs. 16 and 17.)

Table 1. Pertinent test section dimensional quantities

Tunnel	Mach number	h_g, in.	w_g, in	δ, in.	δ^*, in.
SWT	1.3	20.2	18	0.90	0.15
	2.0	20.3		1.15	0.25
	3.0	20.4		1.58	0.48
	4.0	20.6		1.99	0.77
	5.0	21.2		2.51	1.13
HWT	4.0	15.8	19.8	"2.85"	"1.05"
	5.0	18.9		3.00	"1.25"
	6.0	19.5		3.38	1.45
	7.3	20.0		3.57	1.58
	8.5	20.8		3.85	1.95
	9.5	21.1		4.34	2.09
	10.1	23.8		"4.75"	"2.37"
	11.0	26.7		"5.70"	"3.25"

h_g = geometric height at the center of the test section window.
w_g = geometric width at the center of the test section window.
δ = total boundary-layer thickness
δ^* = boundary-layer displacement thickness
$\left.\begin{matrix}\delta \\ \delta^*\end{matrix}\right\}$ at 80% of maximum supply pressure, normal supply temperature.
"( )" = estimated values. All other values are measured quantities.

Operating Conditions

Air is supplied to both tunnels by a compressor plant, which contains eleven centrifugal compressors arranged as shown in the simplified schematic drawings in Fig. 5. The twelfth compressor is of the axial-flow type used to reduce the tunnel supply pressure below atmospheric pressure. Compressors A and B can be connected to compressor L to form a five-stage HWT plant when compression ratio requirements are beyond the capability of the four-stage plant ($M > 9.5$). The electric heater is required in the HWT circuit to furnish sufficient heat to the supply air so that air condensation does not occur in the test section. The HWT after-cooler extracts heat from the low-pressure tunnel exhaust air to about 100°F in order to eliminate compressor and piping problems inherent in compressing hot air.

The operating conditions of the JPL wind tunnels are shown in Figs. 6 to 11. Documentation of operating conditions is a continuing project, which could be adapted to specific needs. The pump-down compressor described above can be connected to either wind tunnel to provide supply pressures below atmospheric pressure at Mach numbers less than 8.5.

The minimum supply pressures available in each wind tunnel are dependent upon model and support system geometries. The pressure can be decreased if the size of the model and associated hardware is minimized or streamlined. The minimum operating conditions indicated in Figs. 6 to 11 are generally for empty test-section conditions.

Operating conditions outside the indicated limits are not necessarily prohibited or impossible. Special consideration will be given to any requests of this nature. As an example, the SWT has been run in an uncalibrated Mach number range varying from 0.3 to 0.7. At these Mach numbers, with small models at small angles of attack, data have been yielded comparable to those obtained in tests run in tunnels specifically designed for these subsonic test conditions.

Nozzle Calibration

The Mach number distribution on the axial centerline of each tunnel is shown in Figs. 12 to 14. The 28 Mach numbers represented are those for which the flow has also been satisfactorily inspected 3 and 6 inches above, below, and to both sides of the centerline, as illustrated in Fig. 15 for $M = 2.4$ in the SWT. Significant insight into typical flow quality above and below the centerline can be gained from Fig. 16, which shows the Mach number and pitot pressure distribution in the vertical plane for several nominal Mach numbers in each tunnel. The total temperature profiles for several Mach numbers in the HWT are shown in Fig. 17. The temperature distributions were measured with a bare wire thermocouple mounted on a vertical traverse. The temperature from the thermocouple T_{TC} has been ratioed to the supply temperature T_0. As noted earlier, the pitot pressure and total temperature cores are essentially the same dimension at any given Mach number in the 20-inch SWT. Since the tunnel supply conditions have a significant effect on the wall boundary layer of the HWT, Figs. 18 and 19 have been included to illustrate the effects of supply pressure and temperature on the Mach number distribution in this tunnel.

One of the unique features inherent in an adjustable, flexible-plate nozzle is its ability to provide any intermediate test section Mach number within the design Mach number range. While a generous number of nozzle shapes have been thoroughly calibrated, the possibility of a new or uncalibrated nozzle shape is always present. It has been demonstrated in the case of the SWT and HWT that there is no problem in obtaining high-quality flow with a new nozzle shape. Figures 20 and 21 show the initial and final flow quality for two Mach numbers in the HWT. ("Initial" in this case refers to a calculated nozzle shape that has been installed and run without experimental corrections. "Final" refers to the accepted operational shape that has been experimentally optimized to provide the best possible flow in the test section. The technique used in designing the JPL nozzle shapes is described in Ref. 3.) Obviously, if calibration time were unlimited, slightly better flow could be obtained for most nozzles. It should be noted that the regular waviness on the centerline Mach number distribution results from scalloping of the flexible plate between jacks. The amplitude of this effect is controlled by the plate thickness, jack spacing, and pressure difference across the plate, and therefore the effect cannot be eliminated by changing the nozzle shape.

When any nozzle shape is run in either tunnel, the pitot pressure, and hence the Mach number, is always determined at an axial station just upstream of the model. In the HWT it is possible to make two nearly vertical pitot pressure surveys simultaneously just upstream of the model. The profiles are in vertical planes located 3 inches to either side of the centerline. Two probes are used to inspect the flow and to permit straddling the tip of a long model. A diagonal trace, such as that shown in Fig. 22, is made several times a day in the HWT in order to inspect the nozzle flow distribution and to determine the test section Mach number whenever the supply conditions are changed. A single probe located 3 inches from the centerline performs this function in the SWT. This technique occasionally saves valuable test time by uncovering ordinarily hidden flow problems caused by a nozzle-seal leak, etc.

It must be noted that in the HWT, because of limited calibration time, it was necessary to optimize a nozzle contour near the maximum supply pressure, where most tests are run. This means that for other supply pressures, substantially less than that corresponding to the optimized contour, the Mach number distribution will deviate in a smooth manner from the optimum obtained. The deviation can be attributed to the change in boundary layer profile. Attention is again called to Fig. 18 for an example of the Mach number variations.

The flow inclination on the centerline in the two tunnels is considered negligible from a practical point of view. In the SWT, it was found to be $\pm$ 0.1 degree or less over the Mach number range. In the HWT the flow inclination is $\pm$ 0.15 degree or less for Mach numbers below 9.0; at Mach numbers equal to or greater than 9.0, it is expected to be slightly larger than $\pm$ 0.15 degree, although this has not yet been verified.

Model Suspension Systems

Although the basic suspension system equipment for the 20-inch SWT and the 21-inch HWT are similar, there are sufficient differences to warrant separate comments for each tunnel. Detailed drawings and structural information relative to the equipment are available and will be furnished on request.

20-Inch Supersonic Wind Tunnel

Basic System. The crescent-type support shown in Fig. 23 can be pitched by remote control from -10 to $+30$ degrees, while its sting socket may be remotely controlled from 0 to 350 degrees. The angle-of-attack range can be varied from -1 to $+39$ degrees by placing a 9-degree offset attachment between the crescent support and the model support sting. It is possible to extend the angle-of-attack range further by fabricating an additional appropriately offset attachment. The pitch rate of the crescent support can be varied from 0.2 to 5.0 degrees per second.

Vertical Traverse. A large traverse attaches to the test section ceiling and, under remote control, can cross the entire test section in a vertical plane. Another remotely controlled attachment can be fastened to the end of the large vertical traverse, providing 22 inches of axial translation relative to the vertical traverse. A small, remotely controlled vertical traverse can be attached to the test section in place of the large traverse. The vertical movement of the small traverse is limited to about 3 inches relative to any manually set starting point. The small traverse is used mainly to survey boundary layers.

Sidewall Mounts. It is possible to replace one or both of the test section windows with equipment which permits supporting models from one or both sidewalls. The remotely controlled angle-of-attack range for a model supported from one sidewall is $\pm$ 27 degrees. Models attached to both sidewalls cannot be pitched easily by remote control. Flow visualization is possible with sidewall supports, although the field of view is limited.

21-Inch Hypersonic Wind Tunnel

Basic System. The crescent-type support shown in Fig. 24 can be pitched by remote control from -10 to $+20$ degrees, while its sting socket may be remotely rolled from 0 to 355 degrees. The angle-of-attack range can be varied from -1 to $+29$ degrees by placing a 9-degree offset attachment between the crescent support and the model support sting. It is possible to shift this 30-degree angle-of-attack range to within any desired limits by fabricating an appropriate offset sting. Whenever the 9-degree offset attachment is used, the remotely controlled roll angle range is -10 to $+270$ degrees. The pitch rate of the crescent support can be varied from 0.2 to 5.0 degrees per second.

Vertical Traverse. The vertical traverse can be installed at any of three axial stations in the ceiling of the test section. The range of travel of the vertical traverse covers the entire height of the test section, and it may be pitched $\pm$ 15 degrees. It is possible to install the traverse so that its pitch plane is orthogonal to the air flow direction. This installation facilitates making surveys in the vicinity of a model and its wake.

Design Requirements

Equations have been derived which will allow the designer to calculate the starting or stopping loads in either facility if the maximum angle-of-attack and dynamic pressure are known. Typically, the tunnel flow is established with a minimized initial supply pressure, hence reducing starting loads. However, the model and equipment must be designed to withstand unscheduled loss of flow at the maximum dynamic pressure corresponding to the desired Mach number range. The following formulas should be used for both tunnels:

Unscheduled Flow Breakdown or Blocking Loads

1. Vertical loads
   Flat surfaces: $L = (0.12\ \alpha + 1.2)qA$
   Round surfaces: $L = (0.06\ \alpha + 0.6)qA$
2. Lateral loads
   Flat surfaces: $L = (0.06\ \alpha + 0.6)qA$
   Round surfaces: $L = (0.03\ \alpha + 0.3)qA$

   where
   α = angle-of-attack, deg (The angle in this computation is restricted to absolute values greater than 1 degree.)
   A = planform area, in.^{2}
   L = load, lb
   q = dynamic pressure, psia
3. Margins of safety shall be positive and based on the ultimate strength of the material.
4. The maximum temperature imposed on the material will determine its ultimate strength.

Aerodynamic Running Loads

1. A safety factor of 2 shall be used, and the allowable stress will be the yield stress of the material.
2. The maximum temperature imposed on the material will determine its yield stress.

Structural Requirements for Use With Internal Strain-Gage Balances

As a result of internal strain-gage balance failures and subsequent analyses of the damages, model weights have been limited to 10% of rated capacity of the balance used (in the vertical plane), and the model center of gravity must be placed within $\pm$ 0.125 inch of the balance-force centerline.

The model's center of pressure should be located between the fore and aft gages and preferably be coincident with the center of gravity. Moreover, it is desirable that the model be constructed of lightweight materials to minimize inertial forces on the balance.

Test Instrumentation

There is a variety of instrumentation available for performing tests in the supersonic and hypersonic wind tunnels. The equipment listed below can display a digital, analog, or visual indication of the quantity to be measured. This information is then collected by data-accumulation equipment, described in the next section. Unless otherwise noted, the equipment can be used in either tunnel.

Force and Moment Measurements

Internal Balances

Six-component, water-cooled strain-gage balances of various capacities are available, ranging from 16 to 200 pounds of normal or side force, 5 to 75 pounds of chord force, and 2 to 30 inch-pounds of rolling moment (Table 2).

Accuracy, ±0.25% of full scale.

Resolution ±0.013% of full scale.

Dynamic Stability

Using free-flight techniques, the model drag and static and dynamic stability measurements can be taken without support interference. A great deal of testing has been performed at supersonic Mach numbers on lightweight, 10-degree half-angle cones with a base diameter of 1.0 to 1.5 inches. For these studies, the drag coefficient was determined to within 3%, the static and dynamic stability to within 6%. For shapes with less oscillation decay, the precise determination of model dimensions, mass, center of gravity, and moment of inertia can be extremely critical. Listed below are some typical accuracies associated with the instrumentation and equipment used on a 15-gram, 10-degree half-angle cone with a 1.0-inch base diameter:

Model dimensional determination, ±0.0005 inch.

Mass measurement, ±0.007% of total mass.

Center of gravity, ±0.08% of model length.

Moment of inertia, ±0.5%.

Angle-of-attack determination, ±0.1 degree.

Using a sting-mounted, air-lubricated bearing to support the model, damping derivatives can be obtained on some models through a wide angle-of-attack range. Data obtained from such an air-bearing are recorded by means of an optical tracker, which can detect a point on the oscillating model to within ±0.02 degree.

Table 2. Internal strain-gage balances and ranges

Balance designation	Normal force, lb		Side force, lb		Rolling moment, in.-lb	Chord force, lb	Pitching moment, in.-lb	Yawing moment, in.-lb	Diameter, in.	
	Fore	Aft	Fore	Aft					Uncooled	Cooled
SGB6-1A	50	50	50	50	20	15	150	125	0.75	1.00
SGB6-2A	50	50	25	25	30	50	150	62.5	0.75	1.00
SGB6-2B	50	50	25	25	30	50	150	62.5	0.75	1.00
SGB6-3	100	100	50	50	20	30	300	125	0.75	1.00
SGB6-4	25	25	12.5	12.5	10	15	75	31.3	0.75	1.00
SGB6-5	75	75	40	40	20	75	225	100	0.75	1.00
SGB6-6	8	8	5	5	2	5	16.8	8.5	0.50	0.75
SGB6-7	75	75	40	40	20	50	157.5	68	0.50	0.75

Pressure Measurements

Multipressure Measuring System (MPMS)

100- and 120-port systems are available. In both systems, it is possible to monitor and record less than the indicated number of ports. General characteristics of the systems are as follows:

Full-scale range, 5 to 1000 psia.
Accuracy, ±0.05% of full scale.
Resolution, ±0.013% of full scale.
Scanning rate for the 100-port MPMS, 2 ports/sec; for the 120-port MPMS, 10 ports/sec.

Fluid manometry of up to 100 tubes in units of 10 is available. The fluid may be either mercury or silicone oil (sp. gr. ≐ 0.94) in any given 10-tube unit.

Pressure Surveys

Point-by-point or continuous surveys may be made by using any one of a number of available transducers. X-Y plotters are also on hand for continuous recording of either kind of survey in a graphic form.

Temperature Measurements

A maximum capacity of 150 thermocouples can be provided. Reference junctions (150°F) are available for any combination of copper, chromel, constantan, alumel, and iron.

Flow Visualization

Optical Equipment

A schlieren system is permanently installed in each tunnel area for use in viewing and photographing density gradients in the test section. Because of the very low test section pressures, the entire light path of the HWT system is enclosed in a tube, which is evacuated to the test section static pressure. This procedure nearly eliminates the adverse effects on flow visualization caused by convection currents in the room and at the warm tunnel windows. Models may be front-lighted for schlieren photos in the SWT and the HWT. A sample schlieren photo from the SWT is shown in Fig. 25. High-speed continuous photography at 120 to 5000 frames per second for recording transient phenomena is available in both tunnels. In addition, still and cinematic photography is available in either black and white or color in both tunnels. Polaroid camera equipment is available for situations in which it is impractical to wait for laboratory film processing.

Shadowgraphs may be made using the schlieren light source on film sizes ranging up to 11 × 14 inches; a sample shadowgraph from the HWT is shown in Fig. 26. Film plates 4 × 5 inches and larger can be exposed while held in place at one of the test section windows.

Visual Indicators

The sublimation of several chemicals can be used in both tunnels to provide an indication of boundary-layer transition on a model.

The ionization probe technique in which an electric corona ionizes the air between the probe and a model, is available for use in either tunnel. The resulting phenomenon can be seen and photographed by ordinary means through a test section window. The technique is capable of indicating flow in the low-pressure regions, where the normal schlieren system has little or no resolution.

The vapor screen technique, which uses condensed air or supply air with a high water content and a light screen, can be applied in the SWT.

Data Acquisition and Processing

Wind tunnel test data are collected automatically using the Wind Tunnel Data Acquisition System shown in Fig. 27. This computer-controlled recording device serves both wind tunnels and the test preparation area. It has a total capability of 30 strain-gage channels, 200 thermocouple channels, and 18 36-bit digital channels. The three signal transmission sites have the following capabilities:

SITE	CHANNELS		
	Strain-gage	*Thermocouple*	*Digital*
20-inch SWT	20	150	6
21-inch HWT	20	150	6
Test preparation area	12	50	6

The channels are scanned and the analog signals conditioned at the sites before being transmitted to the central acquisition area. There, the analog signals are multiplexed, amplified, digitized, and finally sent to the PDP-1 computer memory together with the digital signals for temporary storage (Fig. 28). By means of computer programming, some or all of the data can be sent back to the sites for printout by a line printer operating at a rate of 300 lines per minute; the data are also recorded on magnetic tape for processing. A library of different reduction programs is available for the reduction of data by the PDP-1 computer.

The acquisition of data is completely controlled by the computer, with instructions being initiated at any site. It can be programmed to determine the priority of data acquisition from the three sites, the channel sampling rate of 2000 or 5000 channels per second (depending on the application), the number of scans (i.e., sampling of all channels) desired, and other control parameters. The system is also provided with a visual monitoring panel enabling wind tunnel personnel to check and observe any channel value and preset alarm signals to correspond to the maximum limits of a channel. Figure 29 shows a typical panel used at each site.

All strain-gage and thermocouple channels have electronic frequency cutoff filtering which effectively reduces the frequency response of each channel. The thermocouple channels have fixed cutoff frequencies of 100 cycles per second peak to peak. The strain-gage channels have selectable cutoff frequencies of 2.5, 5, 20 and 100 cycles per second peak to peak. The full-scale signal range of all of the channels is also selectable. The thermocouple channels have full-scale ranges of $\pm$ 5, 10, 20, and 50 millivolts, and the strain-gage channels $\pm$ 2.5, 5, 10, 30 and 50 millivolts. Table 3 gives the 1-hour repeatability characteristics of the data system.

Table 3. Data system repeatability characteristics

Strain-gage full-scale voltage, mv	Error (% full scale) at filter cutoff frequency, cps 2.5	5	20	100
± 2.5	0.05	0.06	0.08	0.16
± 5	0.05	0.05	0.06	0.10
±10	0.05	0.05	0.05	0.07
±30	0.05	0.05	0.05	0.05
±50	0.05	0.05	0.05	0.05
Thermocouple full-scale voltage, mv	**at sampling rate, kc 2**	**5**		
± 5	0.20	0.30		
±10	0.12	0.15		
±20	0.06	0.10		
±50	0.05	0.07		

The raw or reduced data may be presented on magnetic tape, on IBM punched cards, and in tabular or plotted form. Magnetic tape records may be tabulated using a 300-line-per-minute alpha-numeric printer. By the use of an interim IBM 7094 program, the output may also be used to produce plots on a Stromberg-Carlson 4020 cathode-ray tube plotter.

Testing Capabilities

Numerous test techniques and capabilities are available in both the supersonic and hypersonic wind tunnels. Some of these capabilities represent the more conventional types of testing, such as model force-moment determination on a sting-mounted balance. In contrast, free-flight testing, currently used to obtain drag and dynamic stability derivatives, is relatively new. A number of techniques have been developed to take advantage of the rather unique features of the continuous-flow variable-density facilities. A brief cross-section of the general test capabilities associated with both wind tunnels is presented.

Force and moment measurements. With eight strain-gage balances available for testing, a wide range of aerodynamic forces and moments imposed on a model can be measured. Typically, the balance to be used is check-calibrated prior to the test to verify that the balance characteristics and basic calibration have not changed since the balance was last used. To ensure efficient use of the test time allocated, the model pitch rate, which is variable, can be increased to obtain the maximum amount of meaningful data within a given time period. On the other hand, it is possible to preset and maintain the model at a given angle-of-attack and roll angle and to study the resulting information.

Pressure measurements. For tests requiring determination of the pressure distribution on a model surface, two remotely operated pressure systems are available. The Multipressure Measuring System can be used in conjunction with the computer to monitor and record the pressures. For models in which the pressure varies significantly, transducers with different pressure ranges can be selected and used simultaneously to sample and record the data.

Temperature and heat-transfer measurements. Steady-state temperature measurements can be taken with thermocouples attached to the surface of a model. The computer can accept a maximum of 150 thermocouple inputs in 30 or 75 milliseconds. For transient temperature or heat-transfer determination, the thin-skin technique is employed. This test technique requires that the thermocouples be directly attached to a thin model surface (0.015 to 0.050 inch thick). Before data are obtained with the flow established, liquid or gaseous nitrogen is exhausted from a cooling shield located directly upstream of the model (Fig. 30). The nitrogen maintains the model temperature below the recovery temperature to which the model will ultimately be exposed. Using liquid nitrogen, temperatures as low as $-320°F$ can be attained. Immediately after the cooling shield is retracted, thermocouple data can instantly be acquired and logged in the computer. Figure 31 shows a model with the cooling shield retracted.

Free-flight model testing. Considerable interest has been focused on a testing technique developed at the Laboratory. By free-flighting the models, the effect of the model-support inherent in conventional testing has been eliminated. There are two techniques available for testing in both tunnels. The first uses a vertically oriented wire to support the model in the test section, upstream of the windows (Fig. 32). Severing and subsequent removal of the wire permits the model to fly downstream past the windows. The second method utilizes a pneumatic gun to launch the models upstream to the leading edge of the windows (Fig. 33). At that point, the model is decelerated to zero velocity and is subsequently accelerated by the air flow in the downstream direction. Using high-speed motion picture photography to document the flight, drag and static and dynamic stability information can be obtained with both free-flight techniques.

Telemetry measurements. Free-flight base pressure measurements on cones and blunt shapes can be made using telemetry concepts. These experiments, conducted at supersonic and hypersonic Mach numbers, employ the launch gun to inject the model in the airstream.

Multi-gas testing. In order to simulate other planetary atmospheres, carbon dioxide–air mixtures were circulated through the tunnel circuit in a continuous mode. Studies were conducted on models in both wind tunnels with carbon dioxide–air mixtures as high as 85% by volume of mixture.

Low-Reynolds number studies. In the supersonic wind tunnel, many experiments have been run with laminar boundary layers over the entire nozzle. The Mach number and supply pressure at which a laminar boundary layer condition is attainable depend somewhat on the model geometry and associated instrumentation in the test section. At Mach number 3.7, at a supply pressure of 13 centimeters of mercury absolute, and with a flat plate mounted in the test section, laminar boundary layers can be established to the plate leading edge.

References

1. Schurmeier, H. M., *Design and Operation of a Continuous-Flow Hypersonic Wind Tunnel Using a Two-Dimensional Nozzle,* Agardograph 38, May 1959.

2. Herrera, J. G., *Maximum Model-Size Determination and Effects of the Sting Diameter on an Entry Shape and Sphere for Low Supersonic Mach-Number Testing,* Technical Memorandum 33-191, Jet Propulsion Laboratory, Pasadena, California, October 30, 1964.

3. Riise, H. N., *Flexible-Plate Nozzle Design for Two-Dimensional Supersonic Wind Tunnels,* Report 20-74, Jet Propulsion Laboratory, Pasadena, California, June 9, 1954.

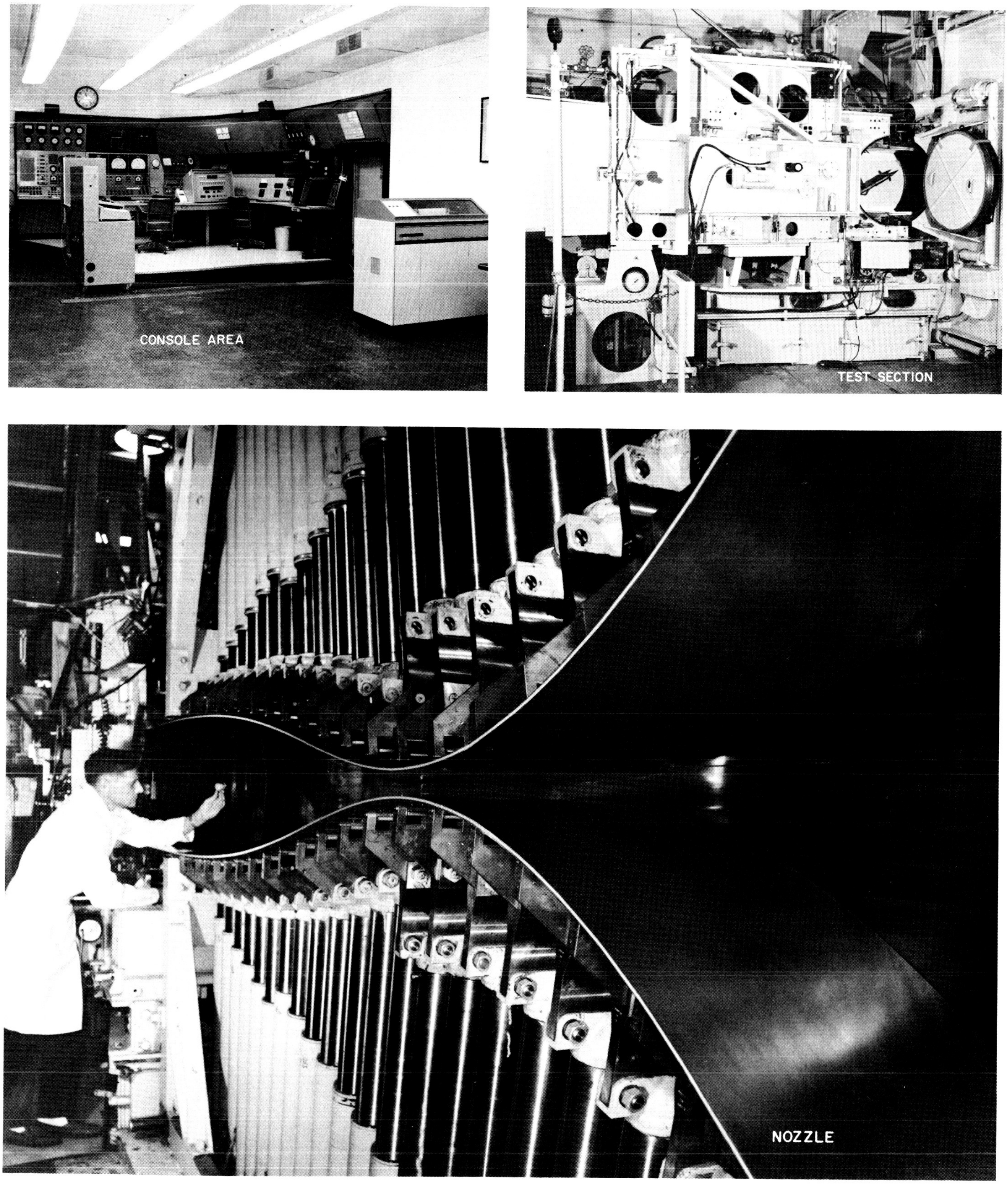
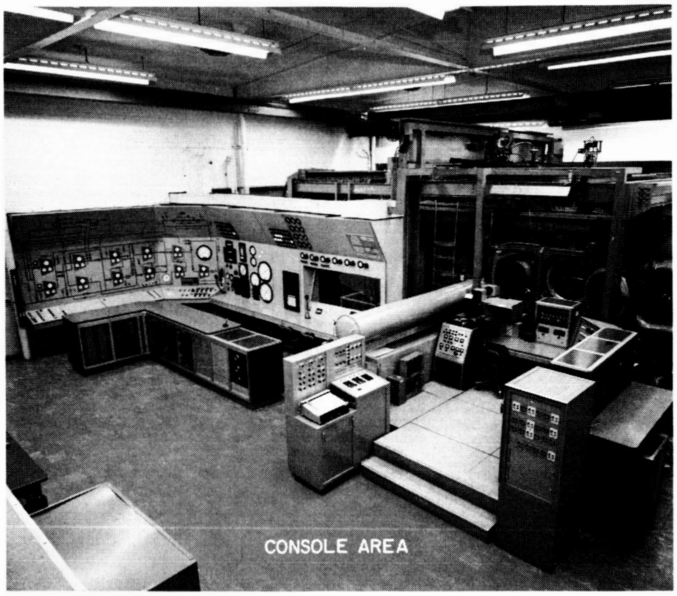


Fig. 1. 20-inch supersonic wind tunnel



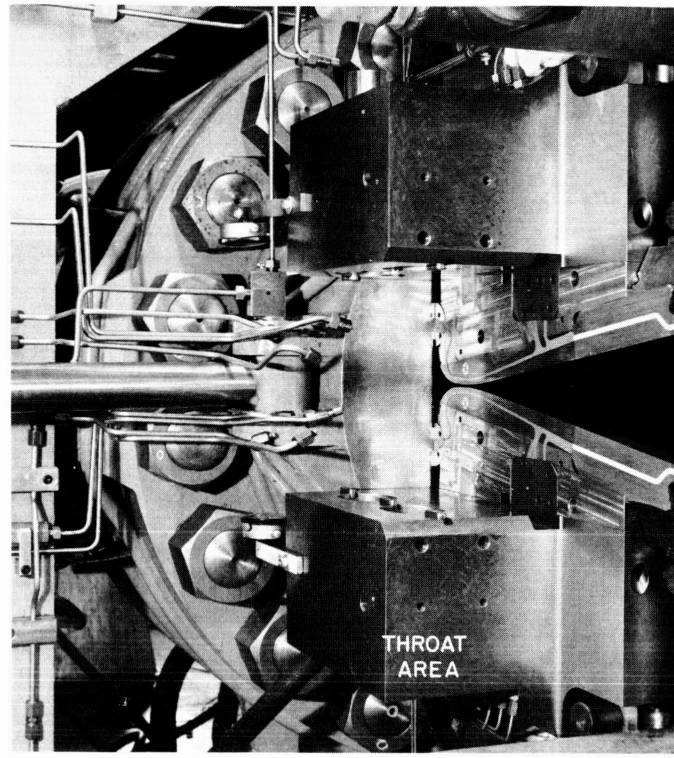
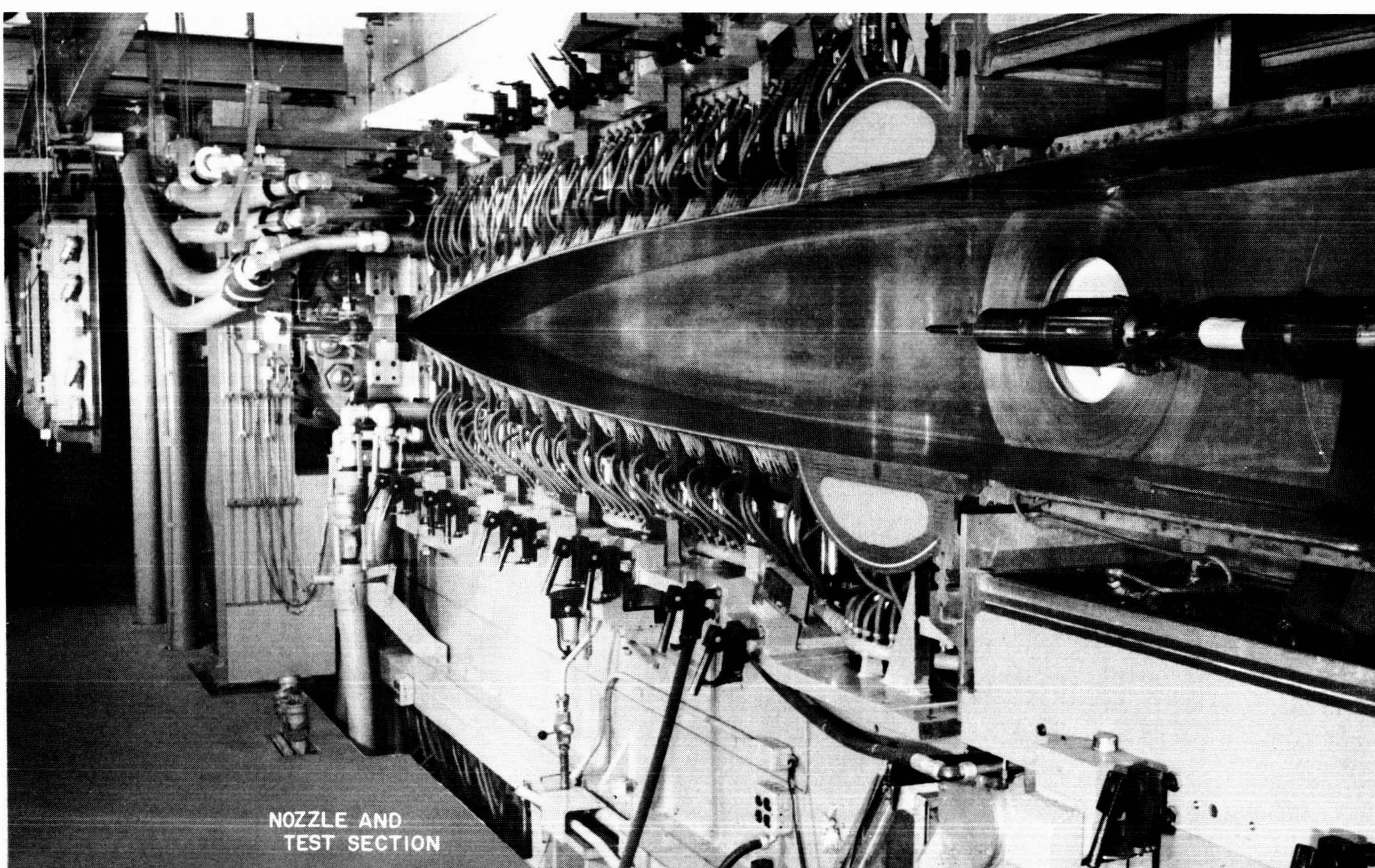


Fig. 2. 21-inch hypersonic wind tunnel



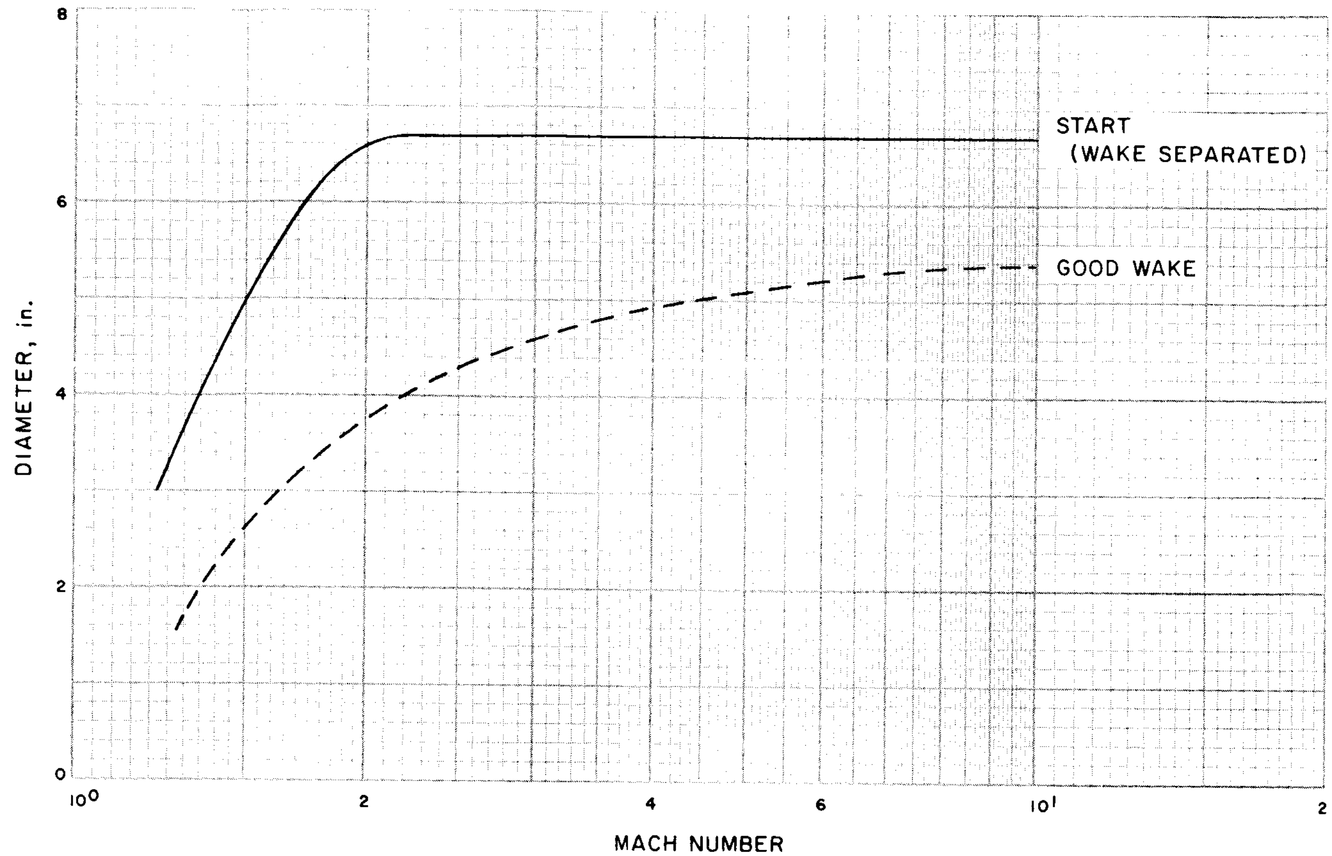


Fig. 3. Maximum sphere diameter that will permit establishment of flow and properly formed wake

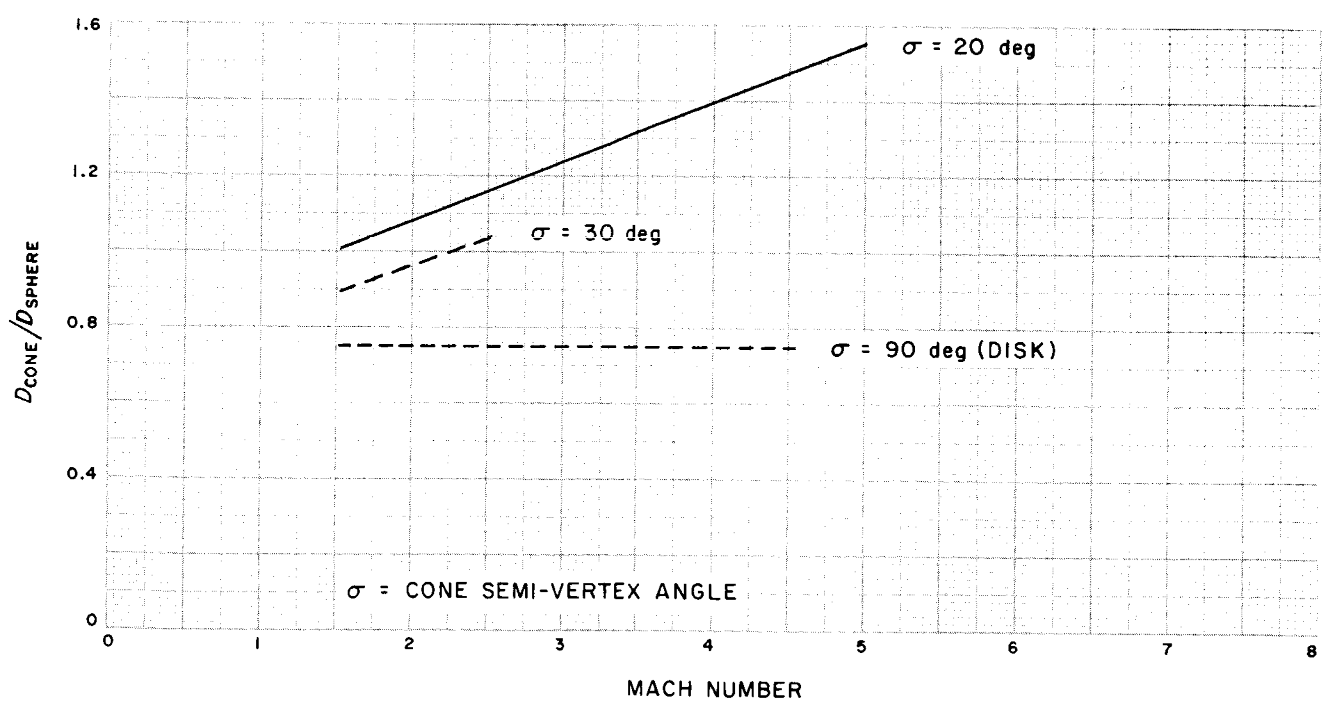
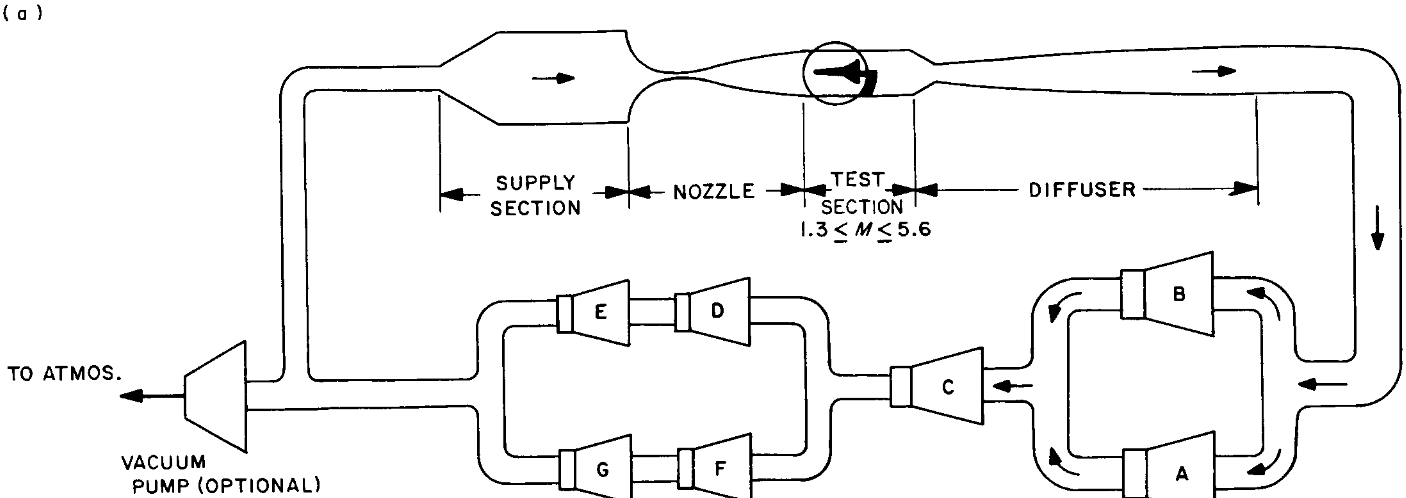


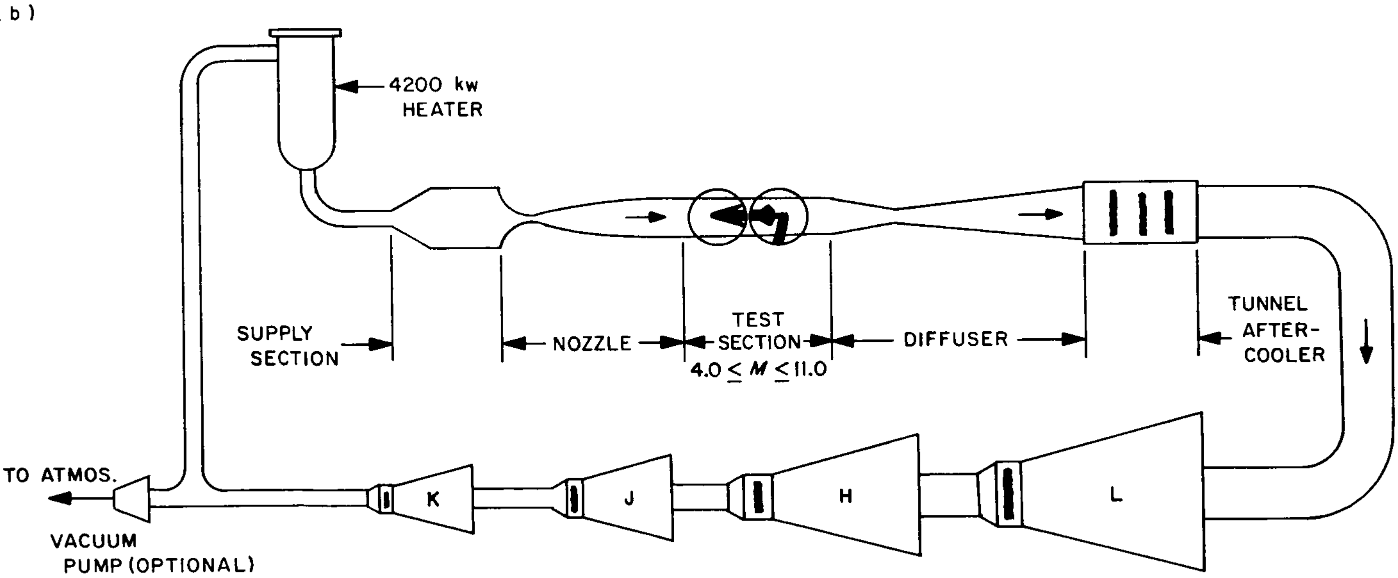
Fig. 4. Ratio of maximum diameter of cone to maximum diameter of sphere for which both models will just allow establishment of flow in the SWT

(a)



COMPRESSOR UNIT	INLET CAPACITY, cfm	COMPRESSION RATIO	DESIGN MAXIMUM PRESSURE, psia	MOTOR, hp
A, B, C	57,000 EACH	2.5:1	36	4,000 EACH
D, F	14,000 EACH	2.1:1	33	1,000 EACH
E, G	8,000 EACH	2.1:1	70	1,000 EACH

(b)



COMPRESSOR UNIT	INLET CAPACITY, cfm	COMPRESSION RATIO	DESIGN MAXIMUM PRESSURE, psia	MOTOR, hp
L	82,000	3.8:1	18	4,000
H	22,000	10.0:1	85	3,000
J	3,500	3.4:1	275	2,000
K	1,075	2.7:1	715	2,000

Fig. 5. Wind-tunnel compressor arrangements

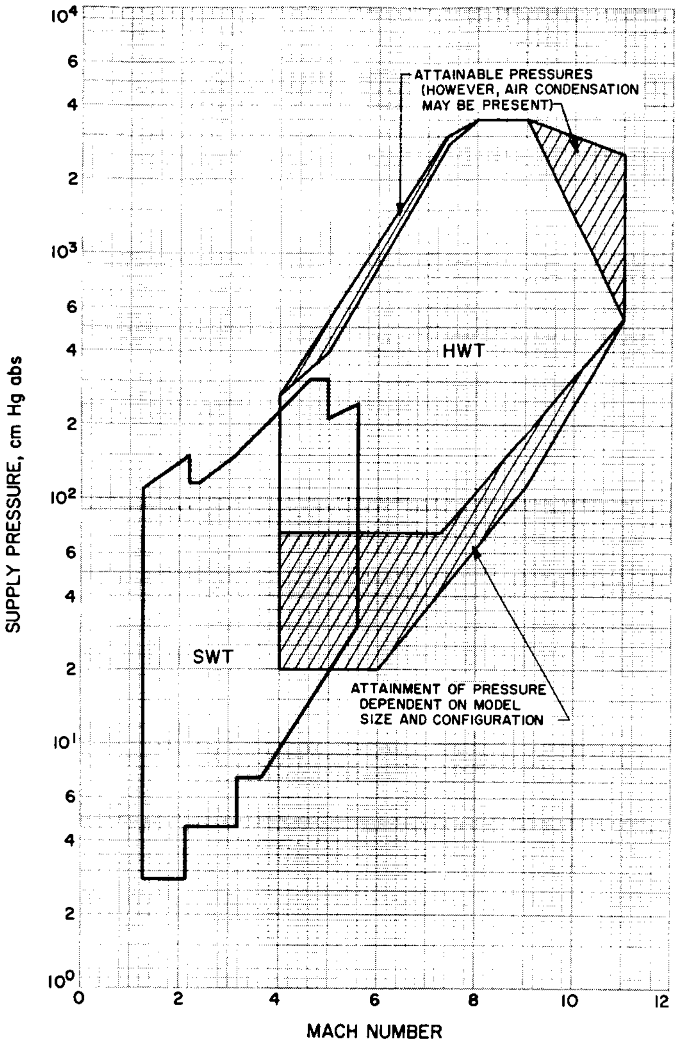


Fig. 6. Available supply pressures and Mach number range in the JPL wind tunnels

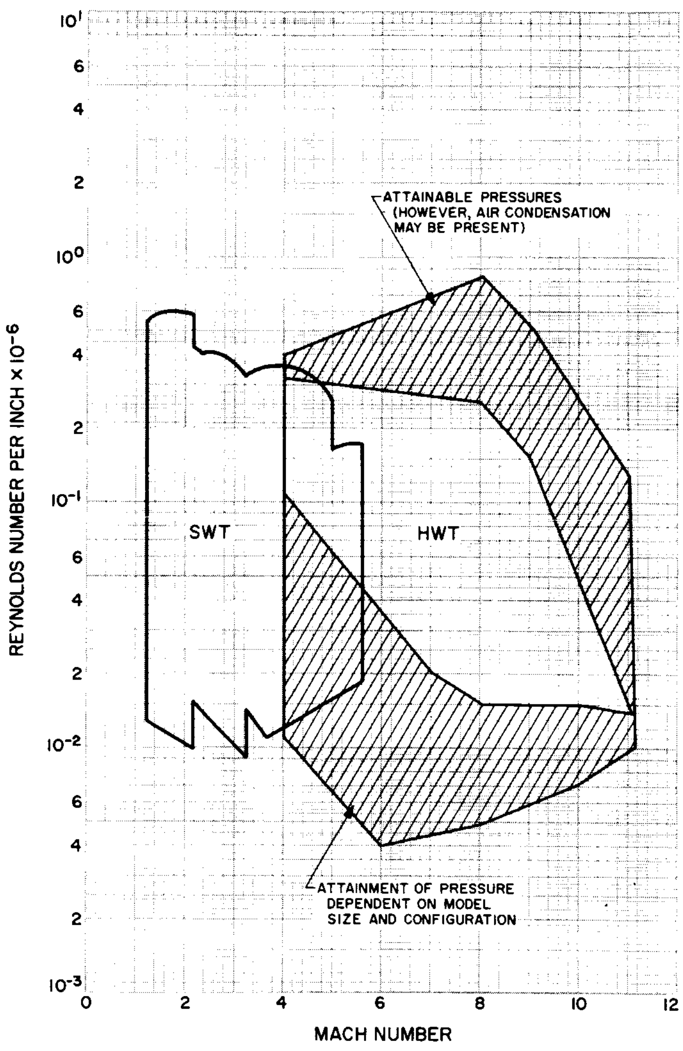


Fig. 7. Test section Reynolds number per inch vs Mach number in the JPL wind tunnels

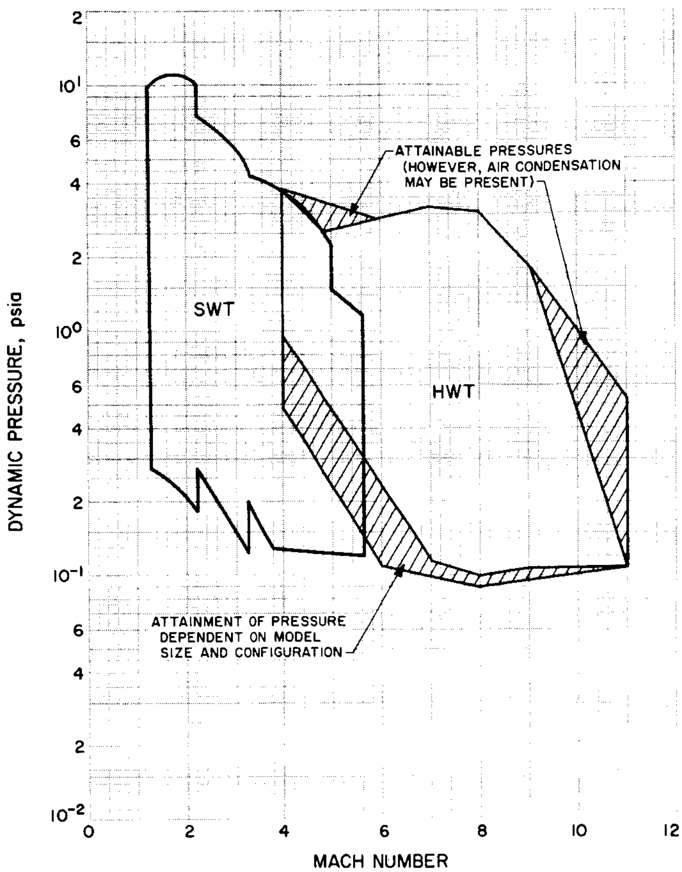


Fig. 8. Test section dynamic pressure vs Mach number in the JPL wind tunnels

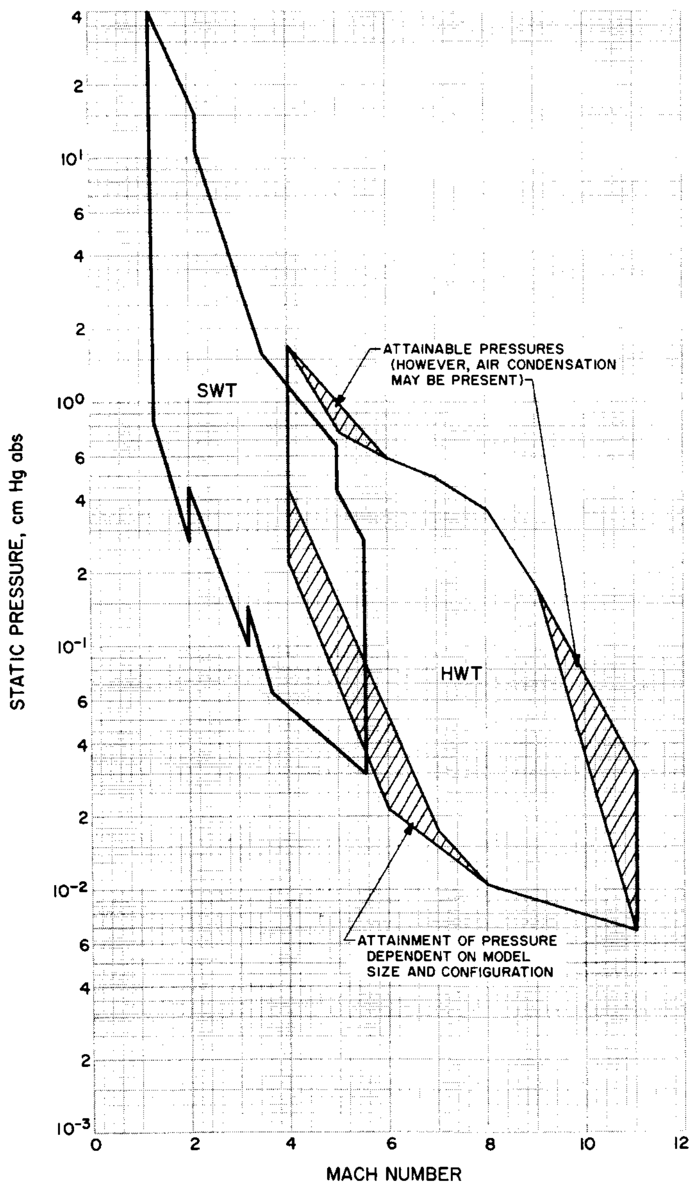


Fig. 9. Test section static pressure vs Mach number in the JPL wind tunnels

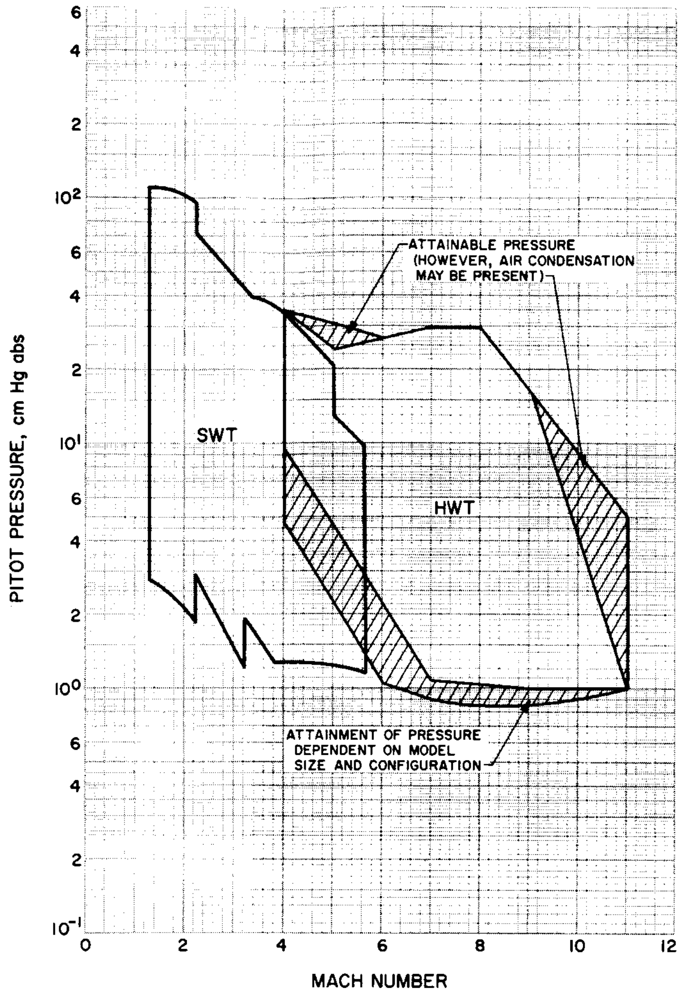


Fig. 10. Test section pitot pressure vs Mach number in the JPL wind tunnels

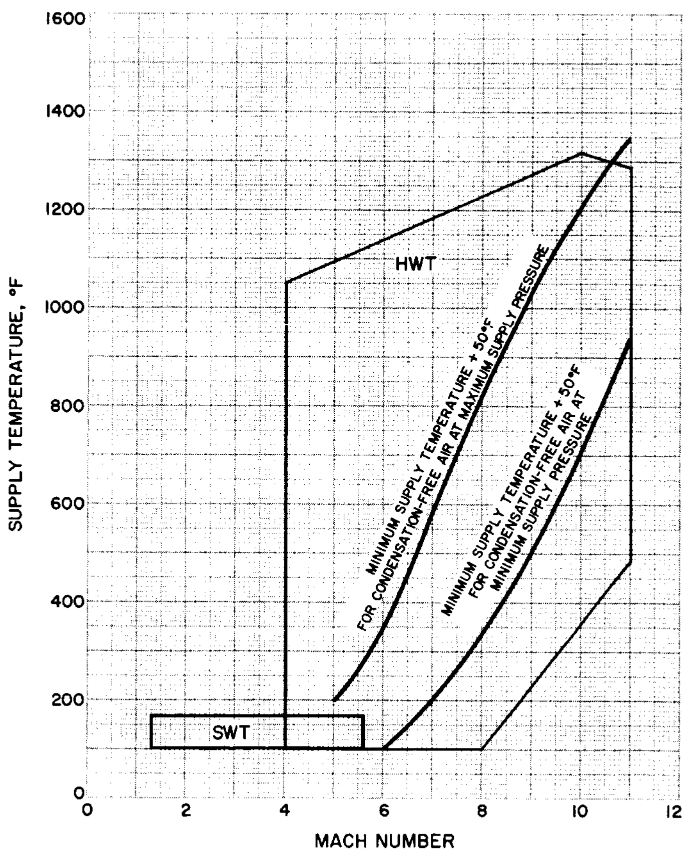


Fig. 11. Available supply temperature vs Mach number in the JPL wind tunnels

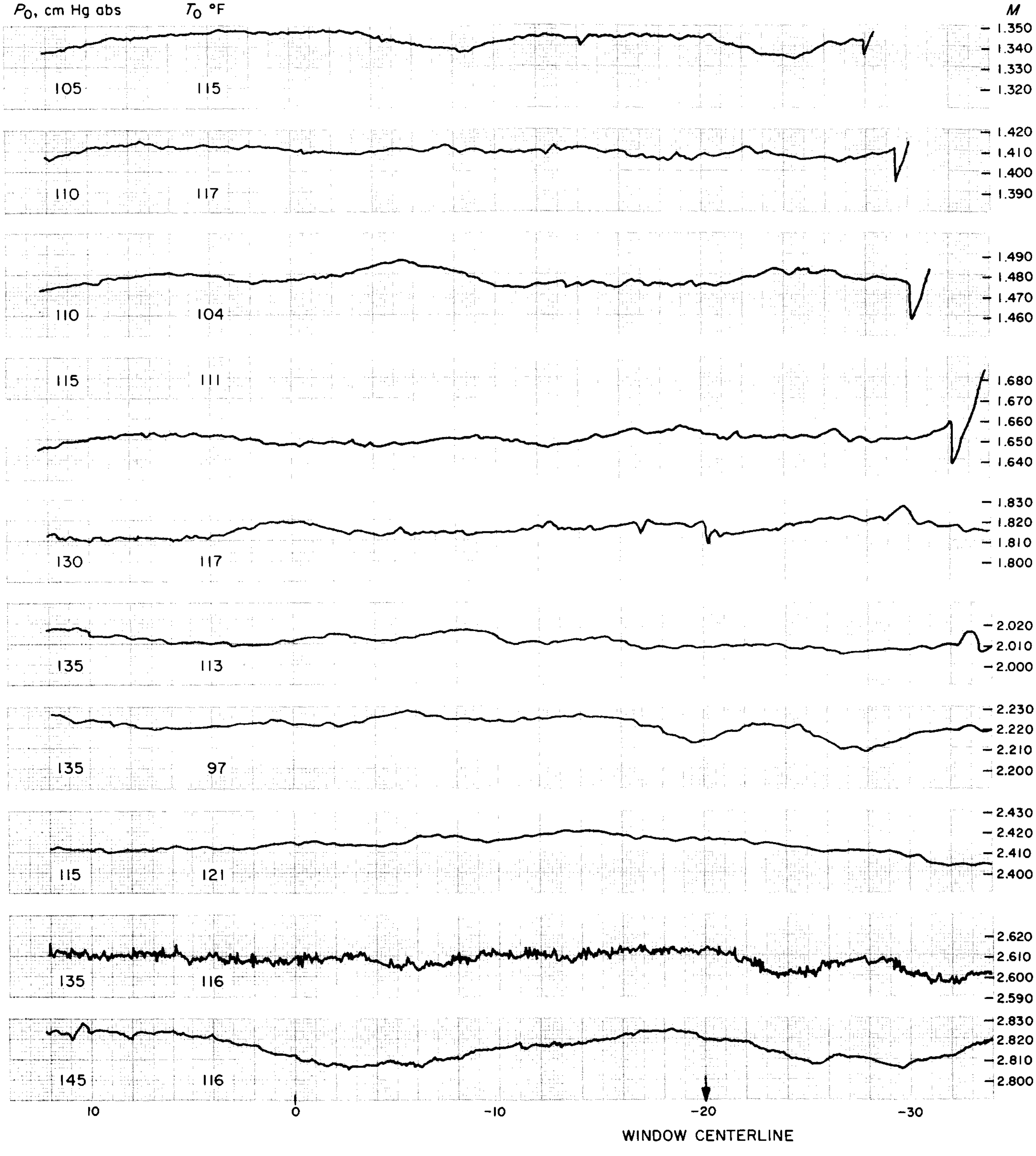


Fig. 12. Mach number distributions on centerline in the 20-inch SWT for M = 1.3 to 2.8

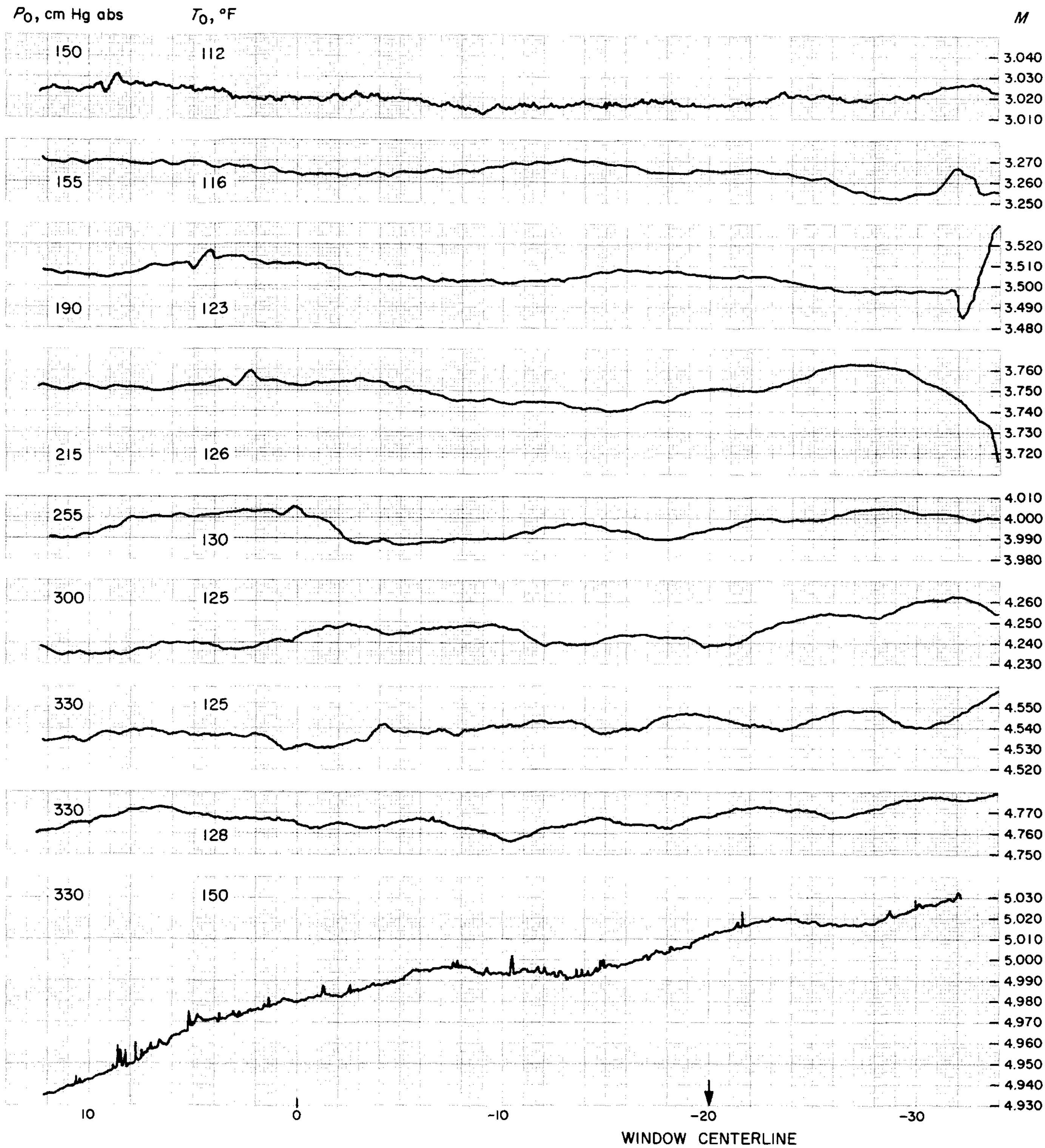


Fig. 13. Mach number distributions on centerline in the 20-inch SWT for M = 3.0 to 5.0

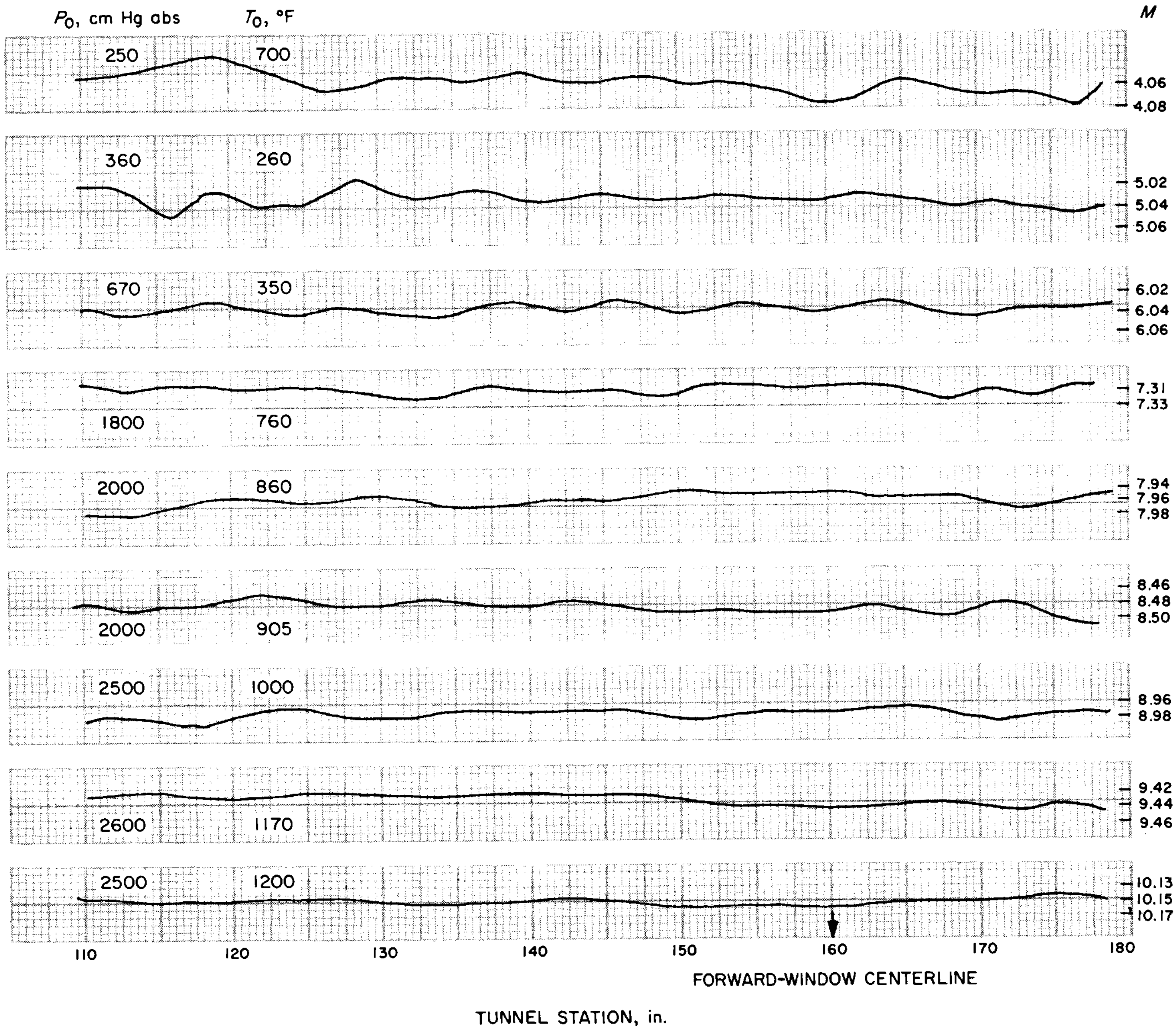


Fig. 14. Mach number distributions on centerline in the 21-inch HWT for M = 4.0 to 10.1

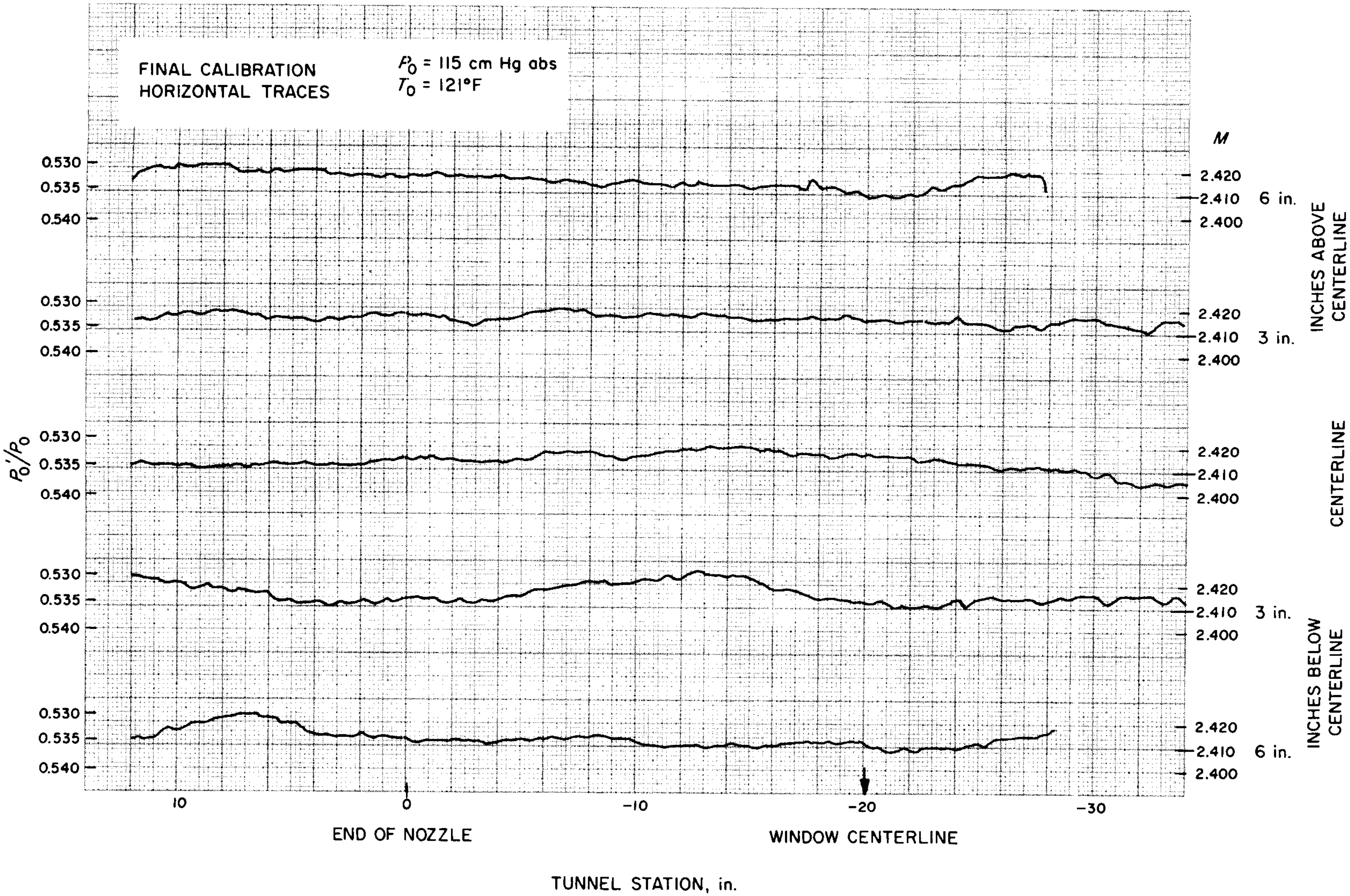


Fig. 15. Complete Mach number distributions in the 20-inch SWT for $M = 2.4$

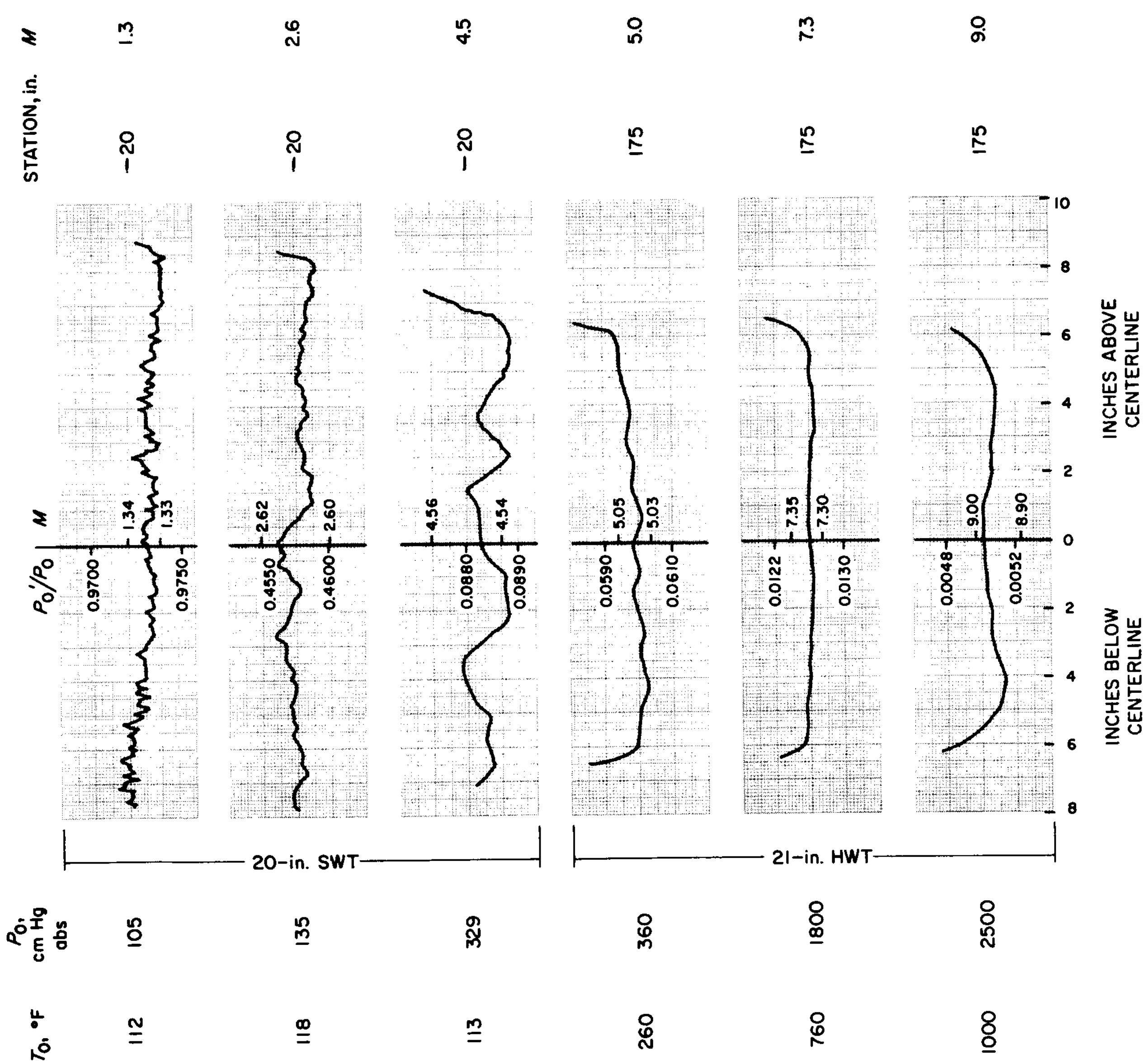


Fig. 16. Mach number distributions in a vertical plane in the test sections of the 20-inch SWT and 21-inch HWT

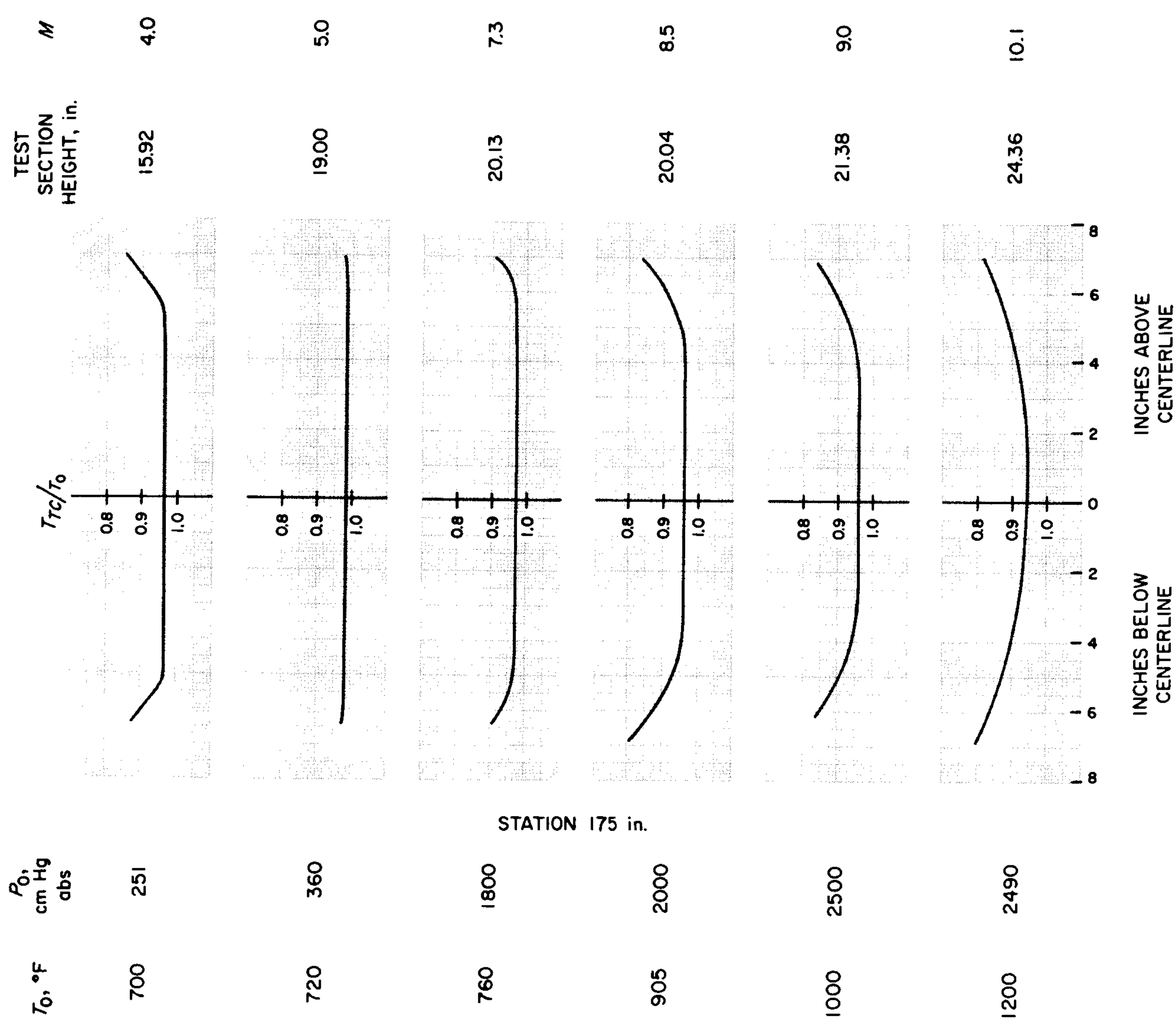


Fig. 17. Temperature distribution in a vertical plane in the test section of the 21-inch HWT

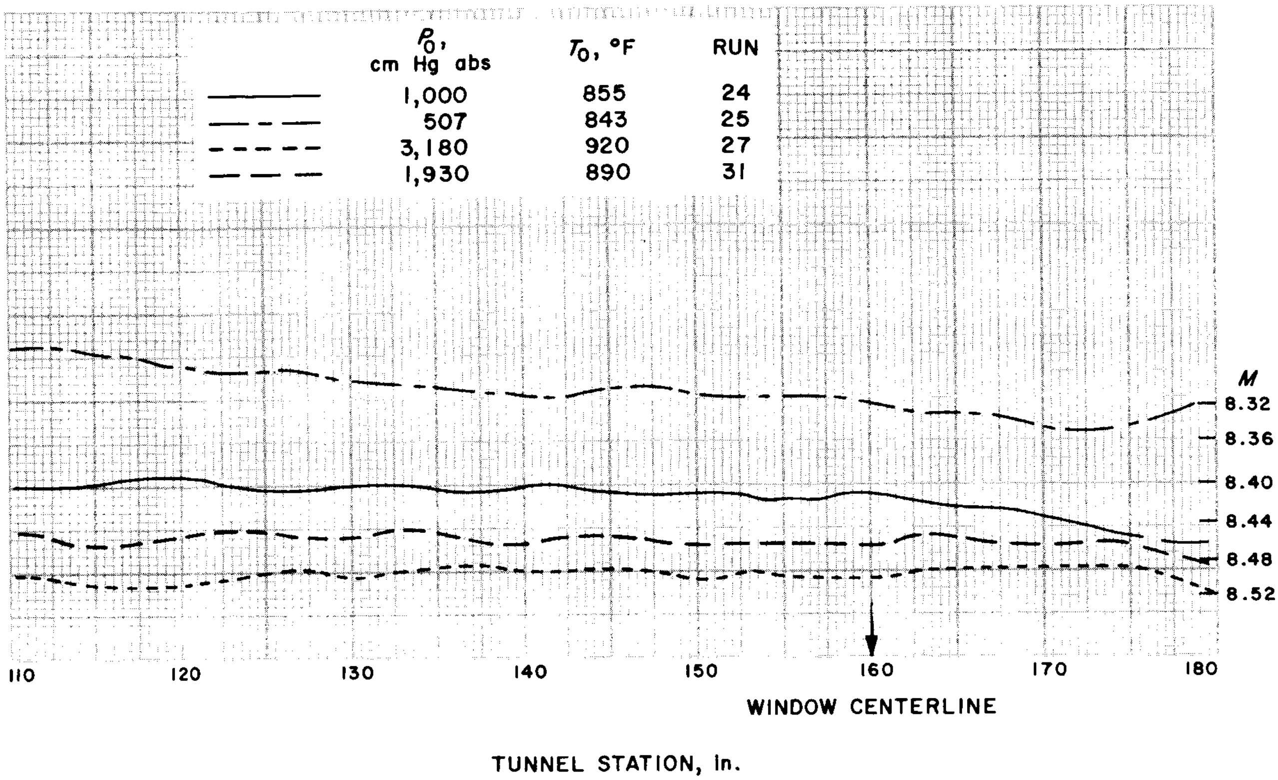


Fig. 18. Effect of supply pressure on the Mach number distribution on centerline in the $M = 8.5$ nozzle of the 21-inch HWT

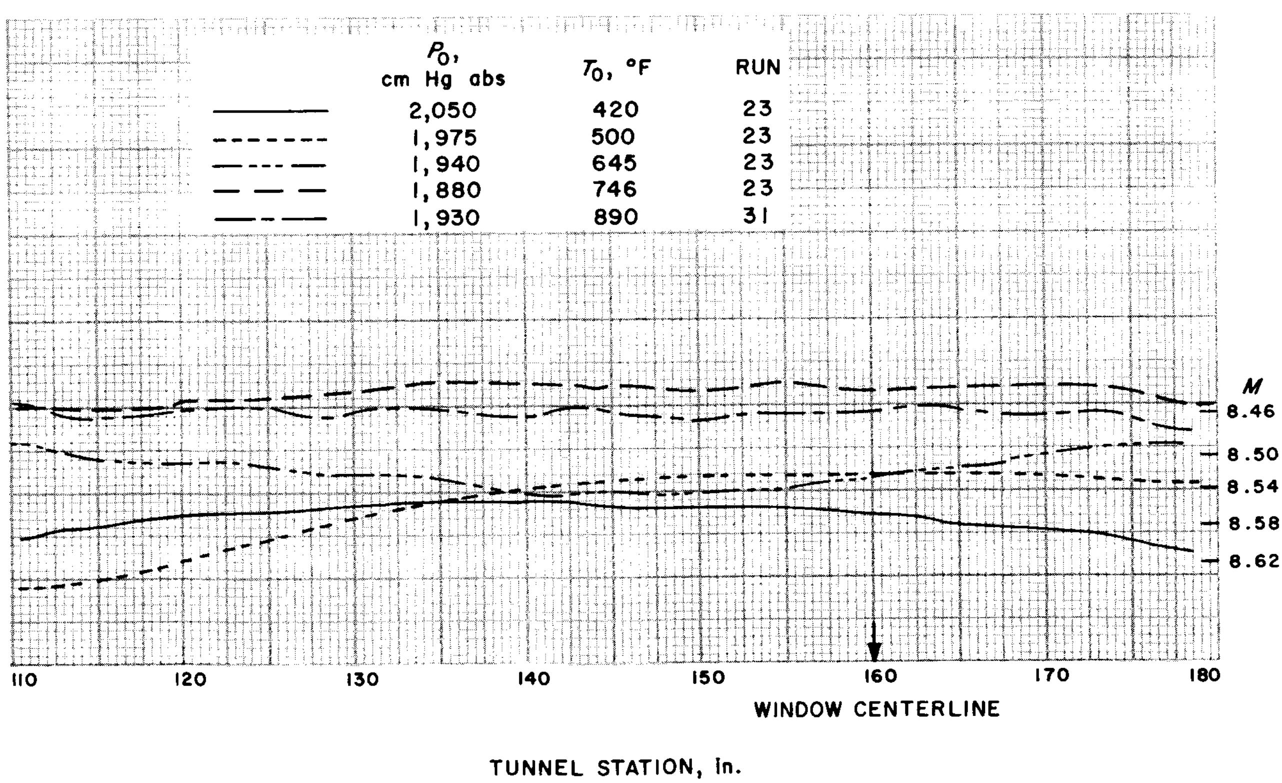


Fig. 19. Effect of supply temperature on the Mach number distribution on centerline in the $M = 8.5$ nozzle of the 21-inch HWT

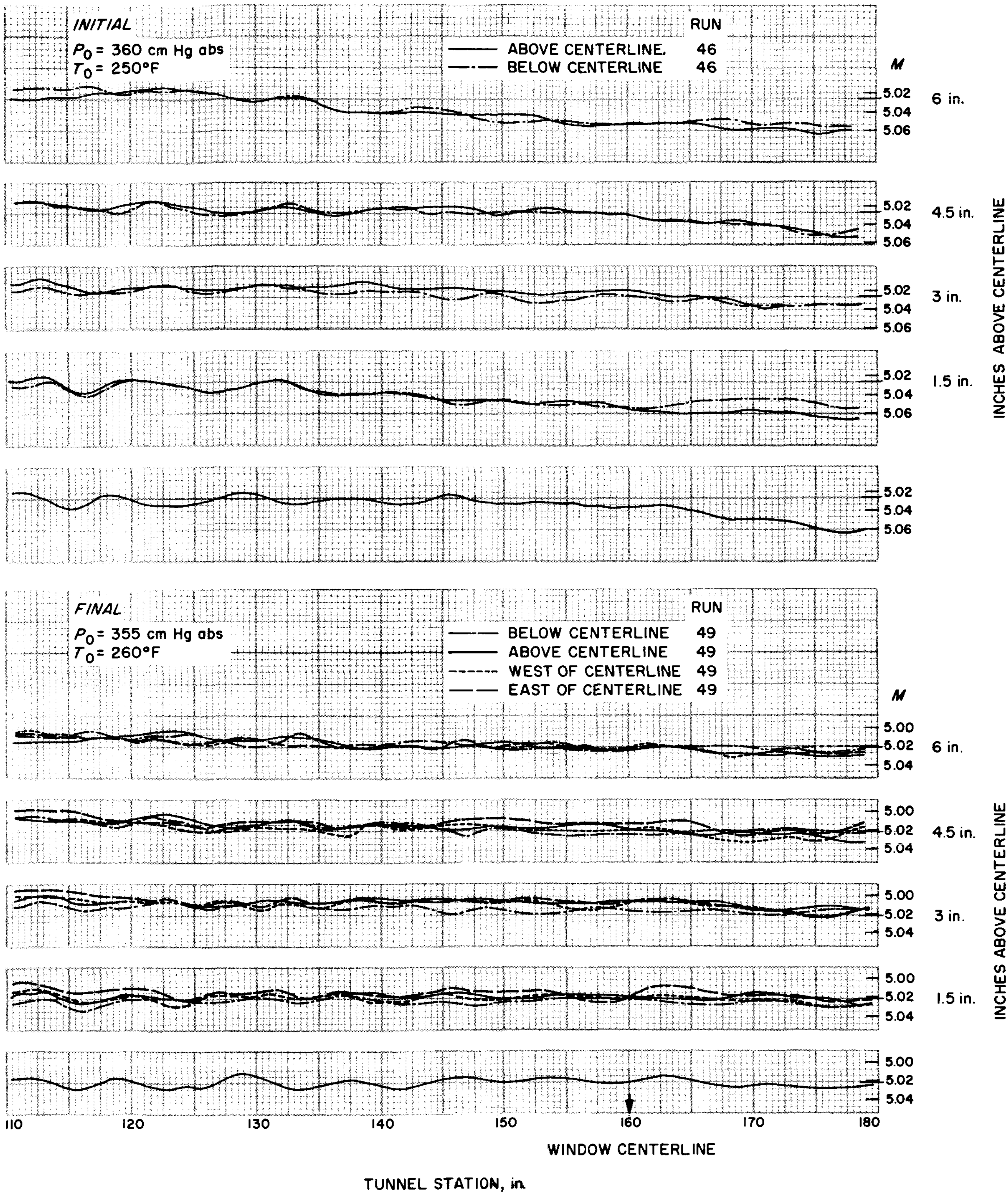


Fig. 20. Comparison of initial and final Mach number distributions in the M = 5.0 nozzle of the 21-inch HWT

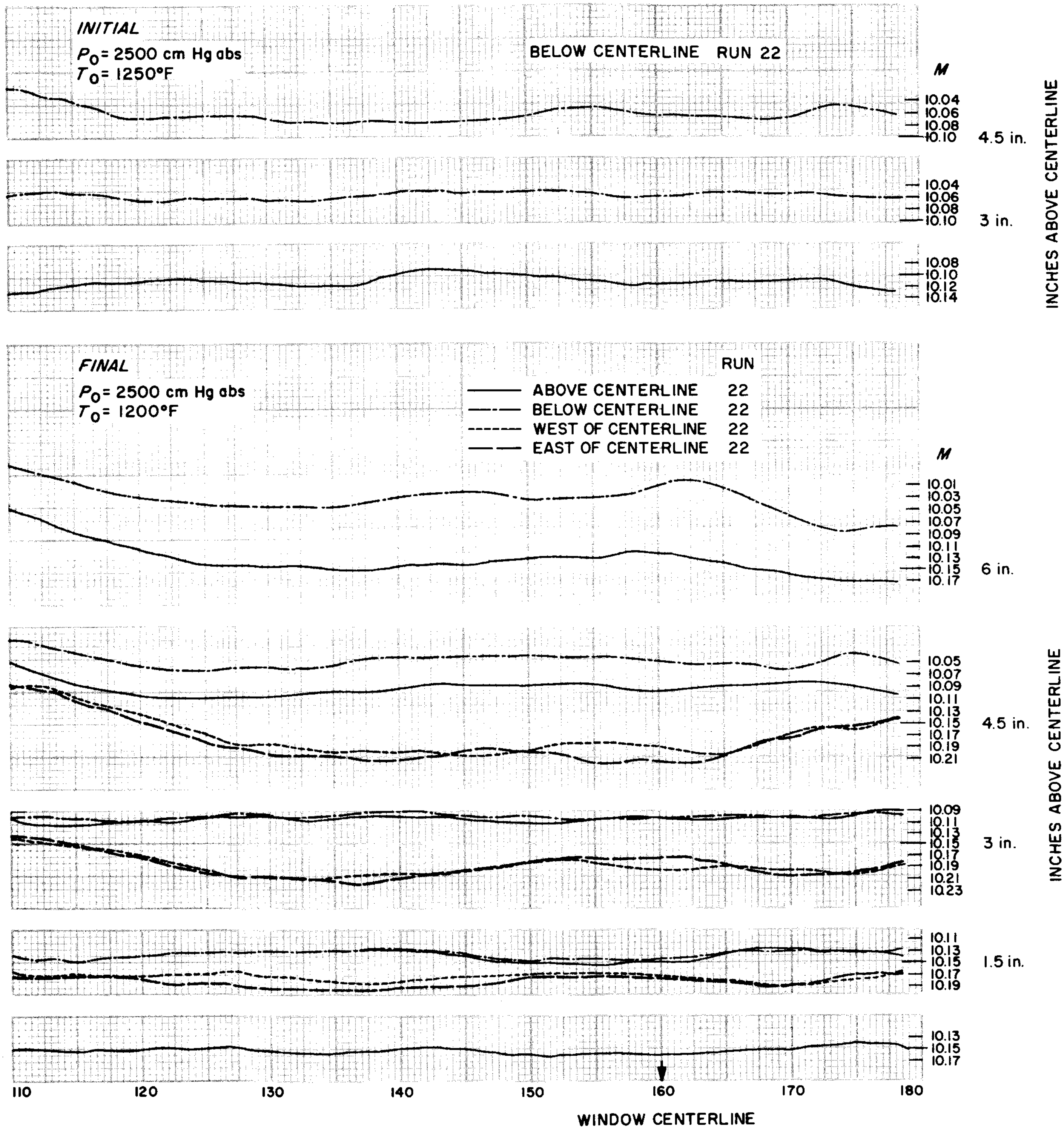


Fig. 21. Comparison of initial and final Mach number distributions in the $M = 10.1$ nozzle of the 21-inch HWT

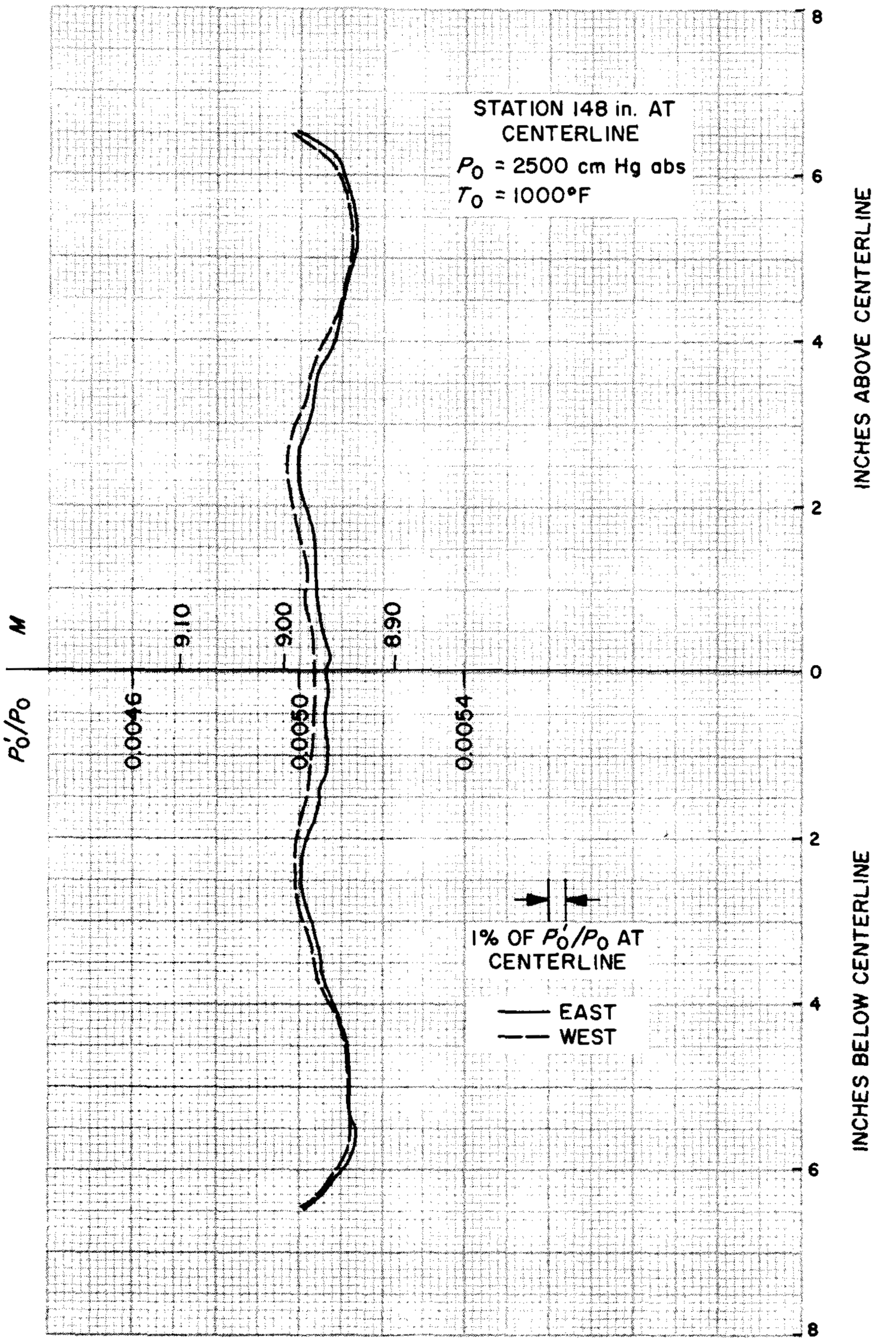
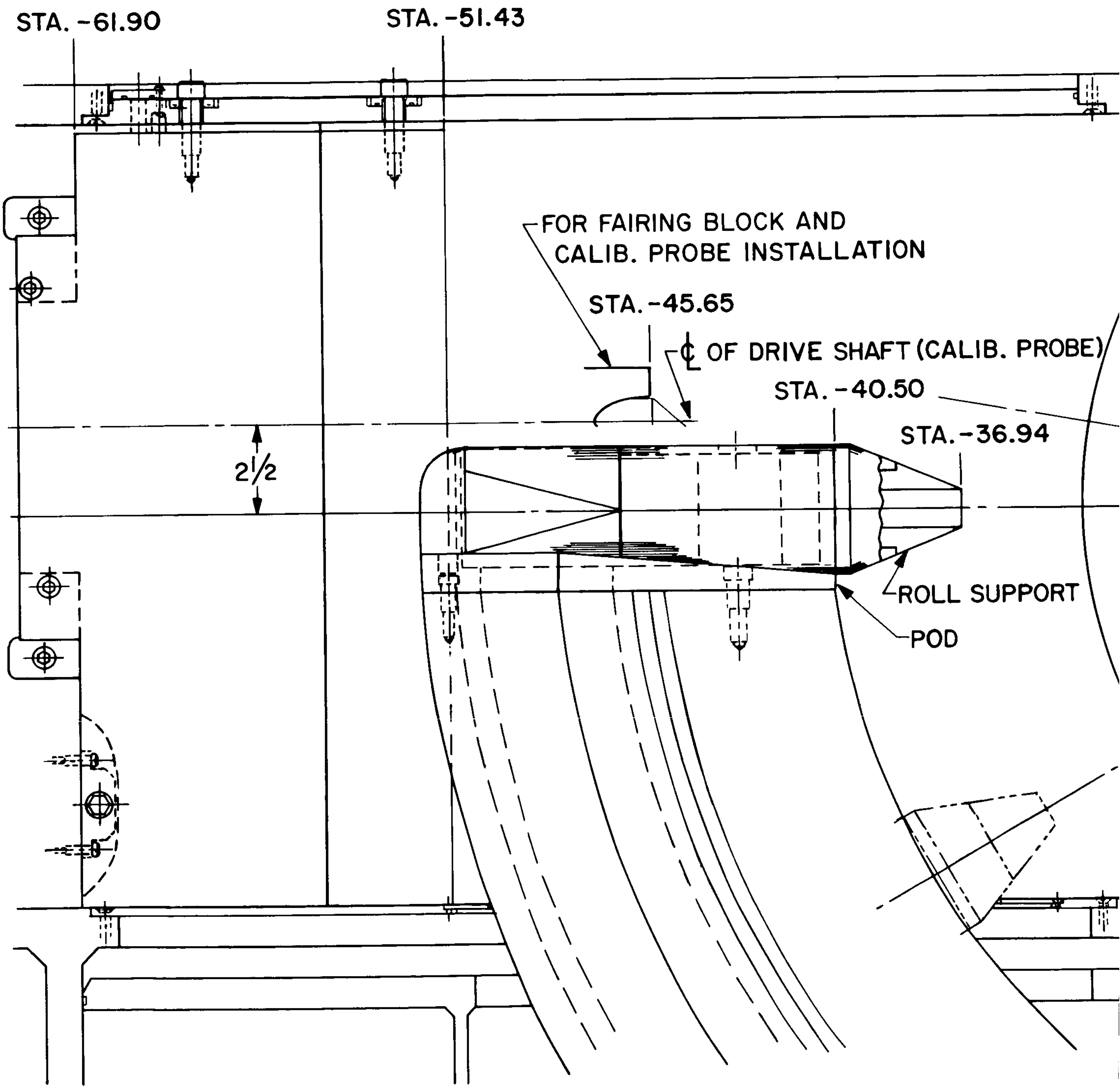


Fig. 22. Sample diagonal trace at M = 9.0 in the test section of the 21-inch HWT

PRECEDING PAGE BLANK NOT FILMED.

ALL DIMENSIONS IN INCHES



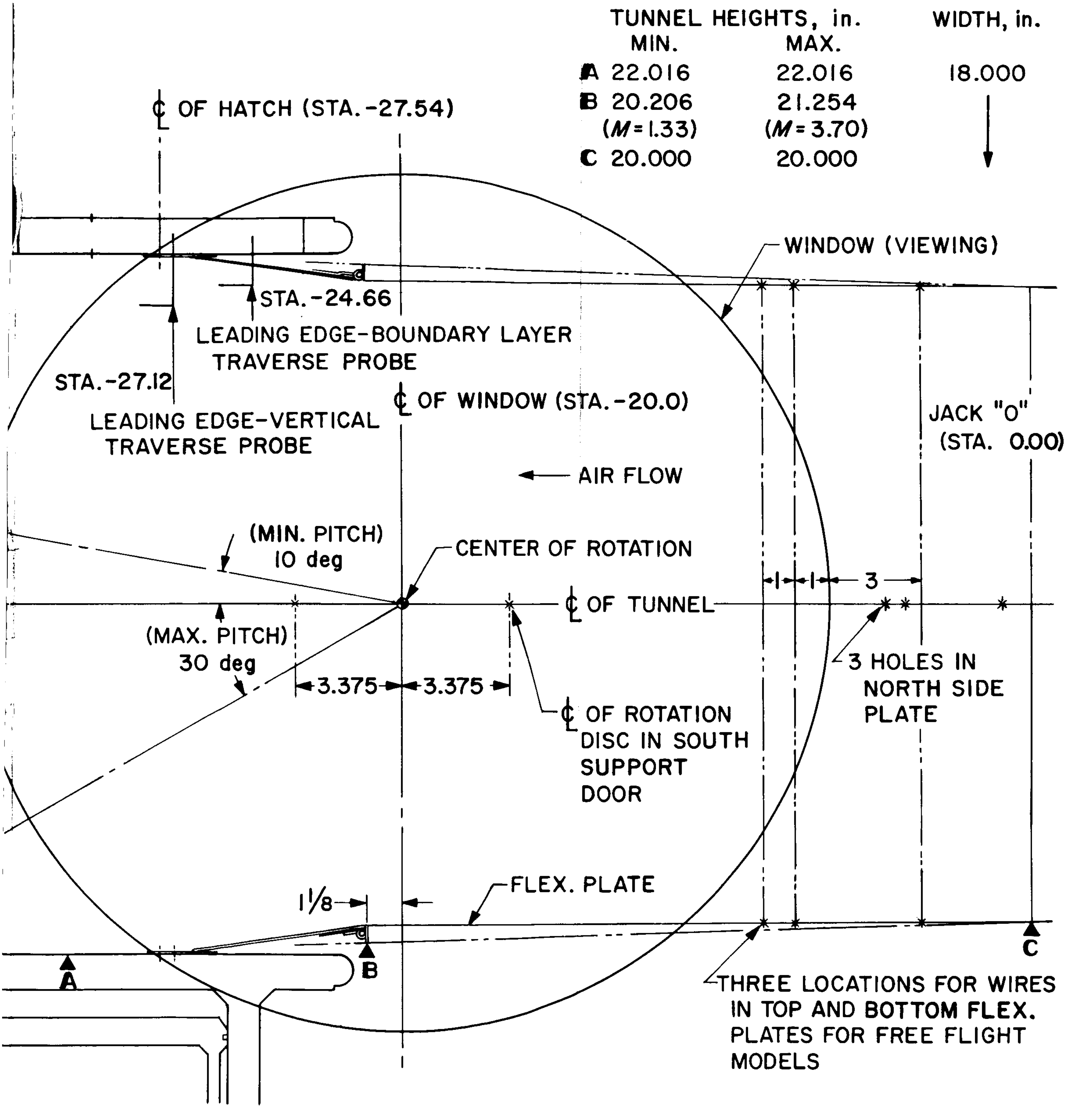
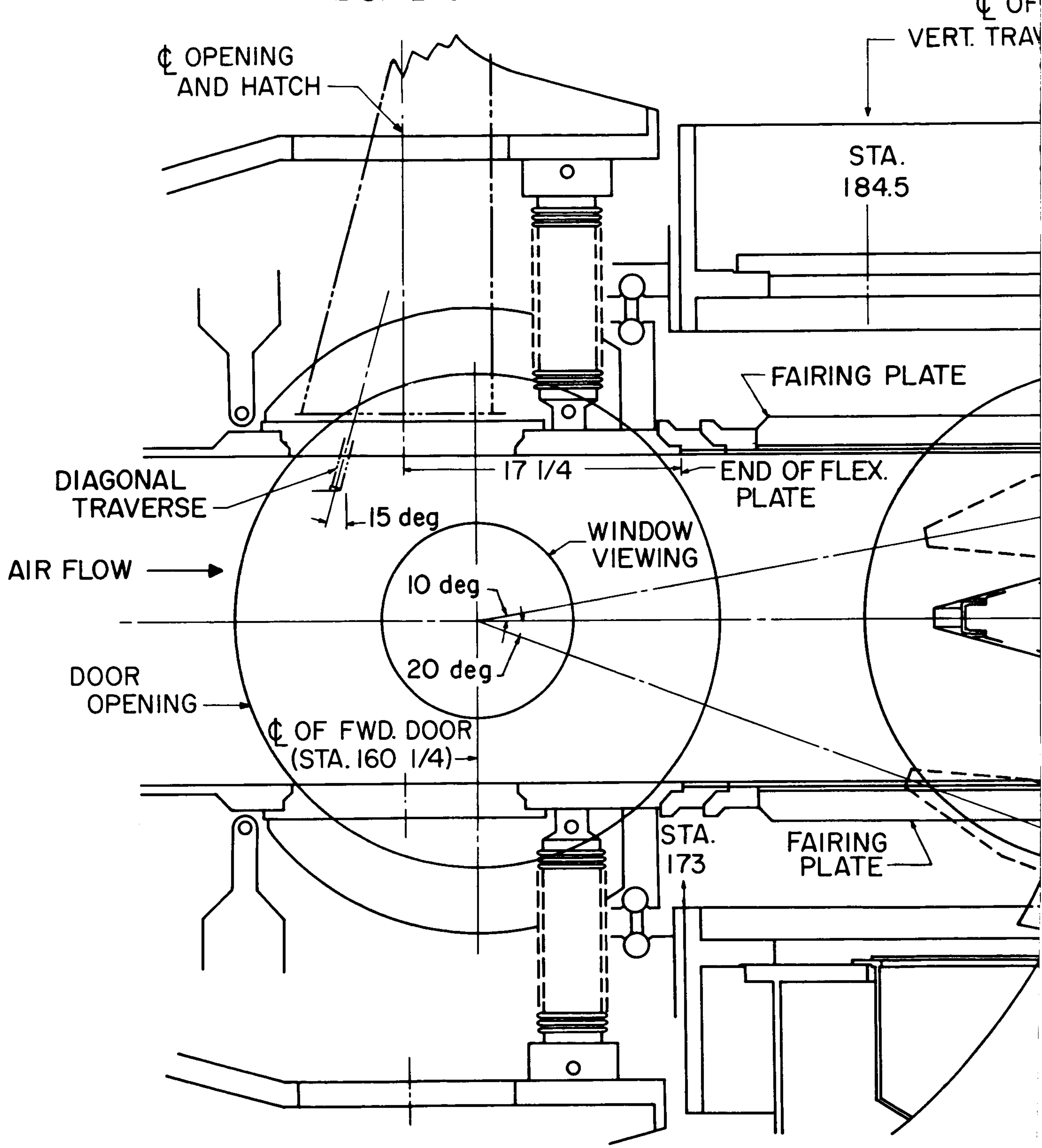


Fig. 23. 20-inch SWT basic model suspension system

ALL DIMENSIONS IN INCHES



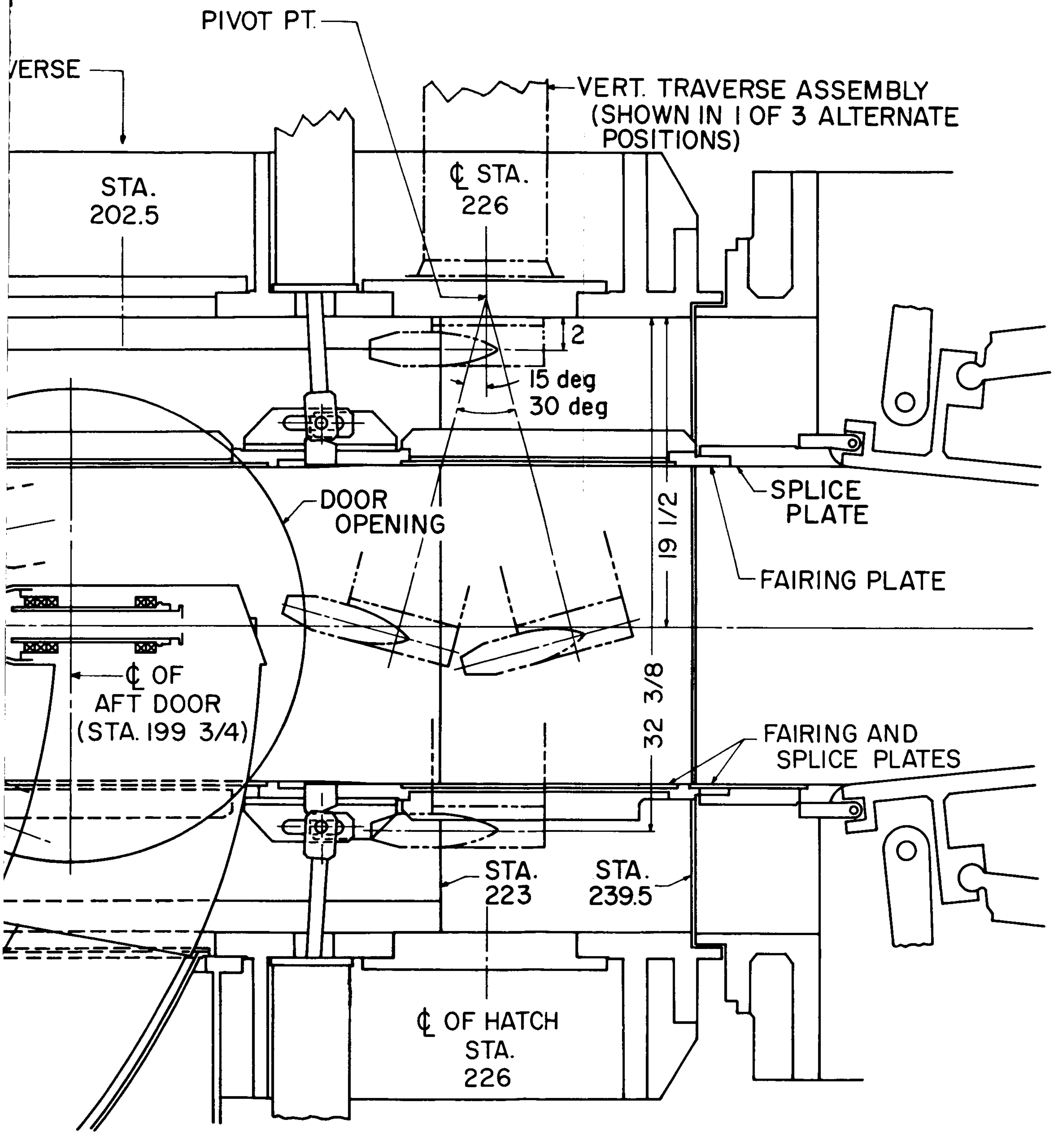


Fig. 24. 21-inch HWT basic model suspension system

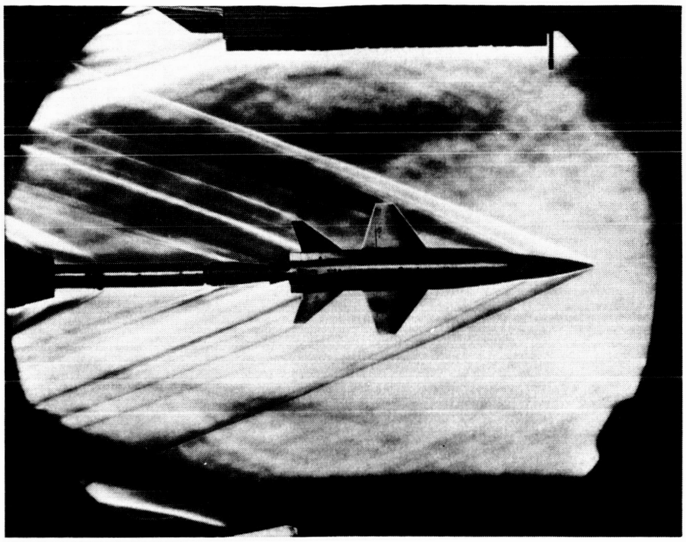


Fig. 25. Front-lighted schlieren photograph of an x-15 airplane in the 20-inch SWT at $M = 3.0$

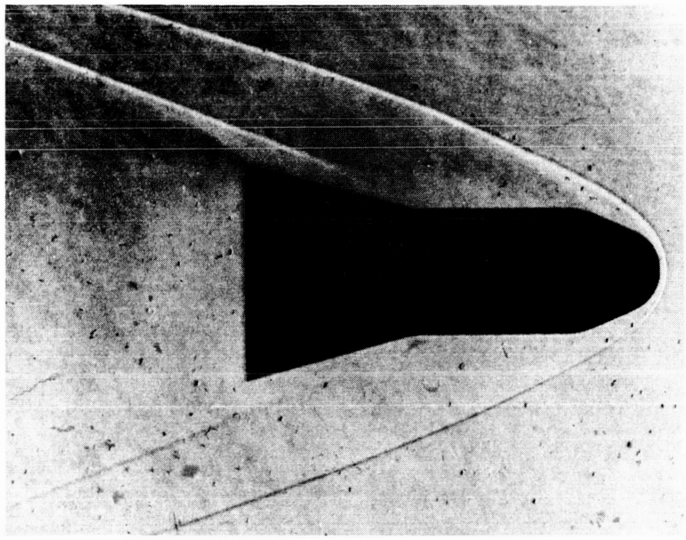


Fig. 26. Shadowgraph of a blunt-cylinder-flare model in free-flight in the 21-inch HWT at $M = 5.0$

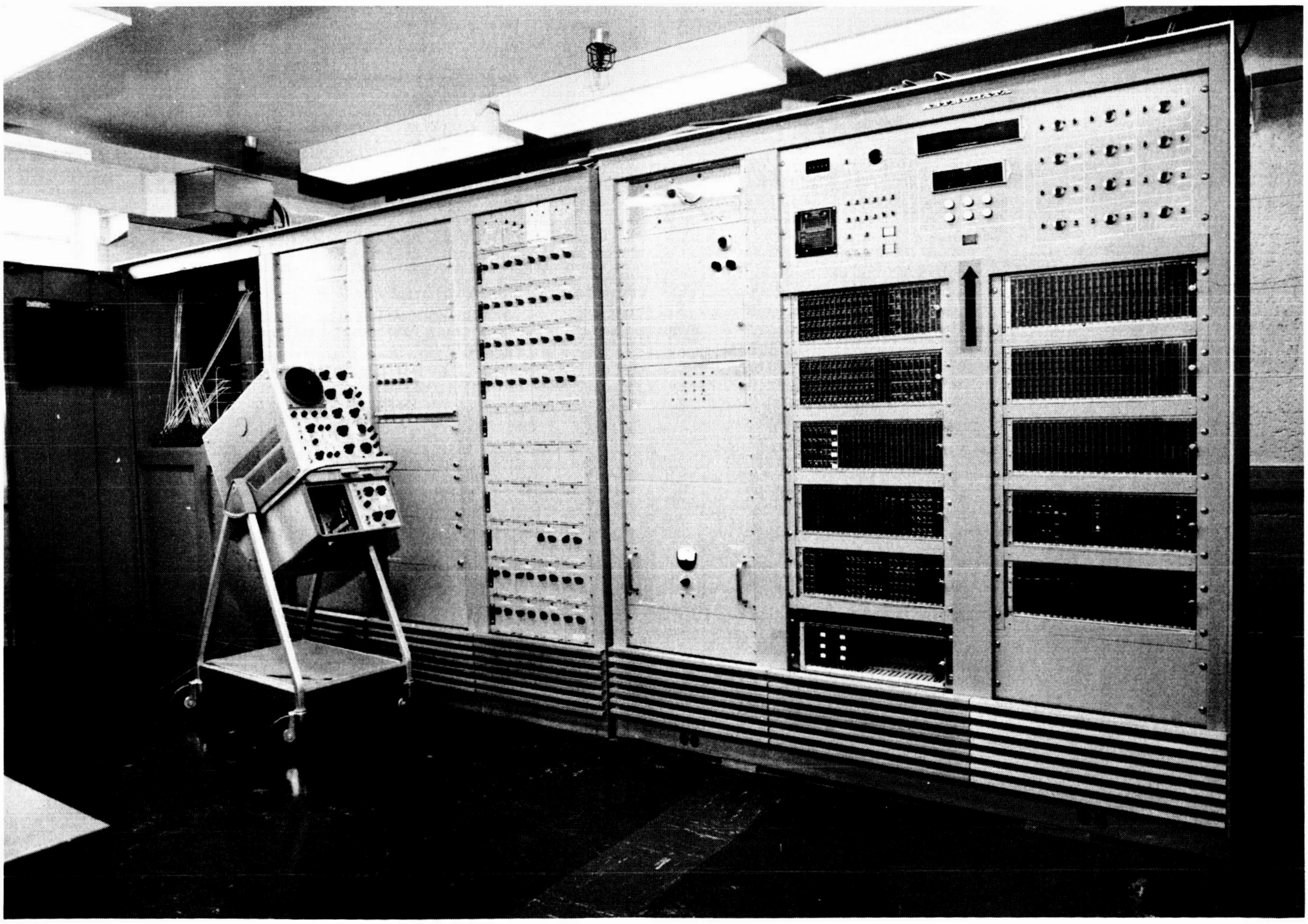


Fig. 27. Wind tunnel data acquisition system

Fig. 28. PDP-1 computer

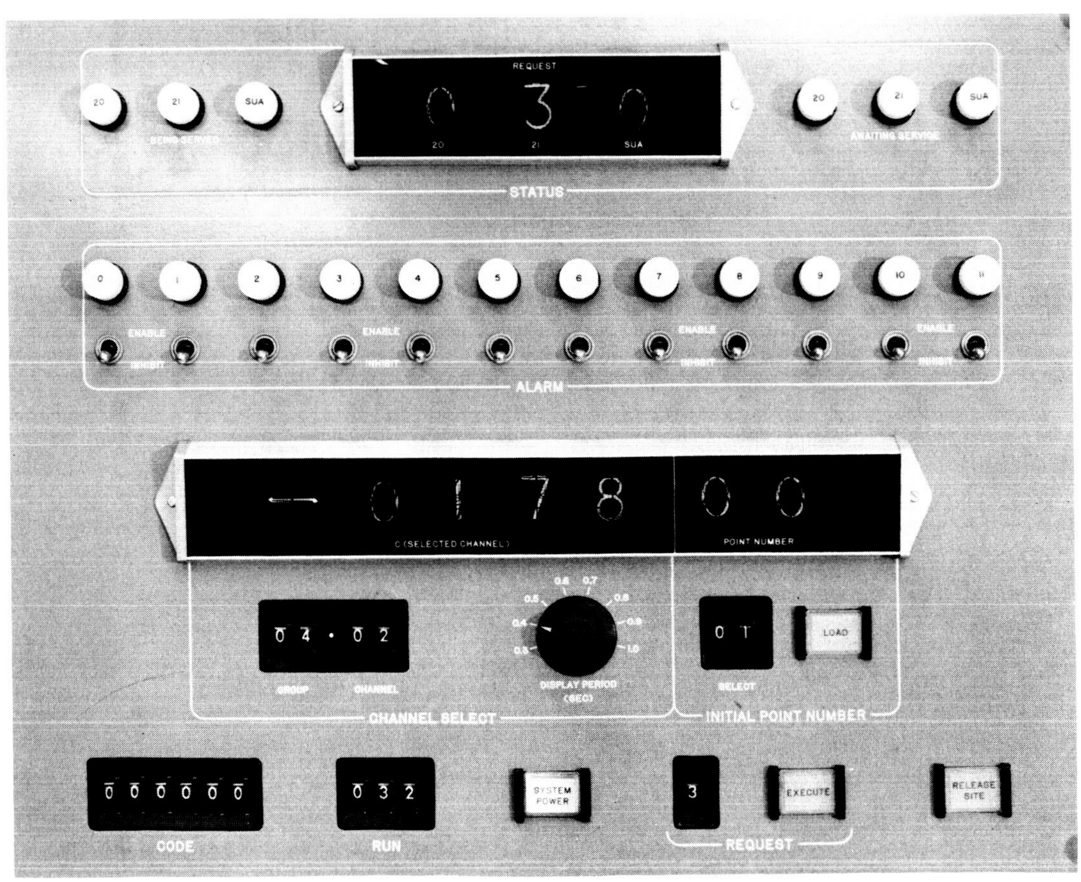


Fig. 29. Data system control panel

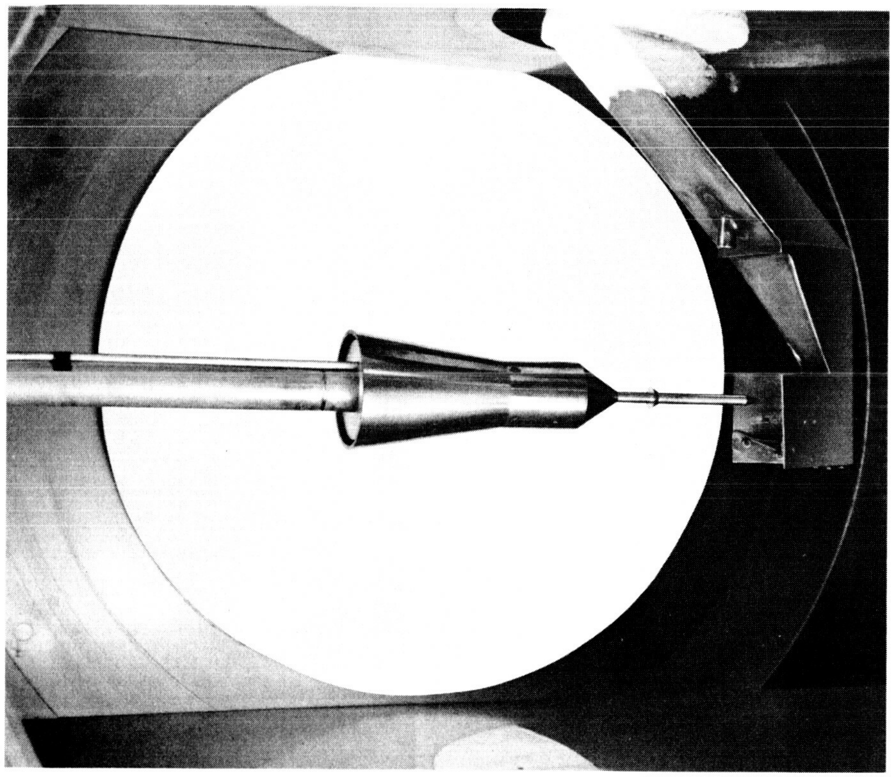


Fig. 30. Cooling shield in position to exhaust nitrogen over a portion of a ***Saturn*** model in the 21-inch HWT

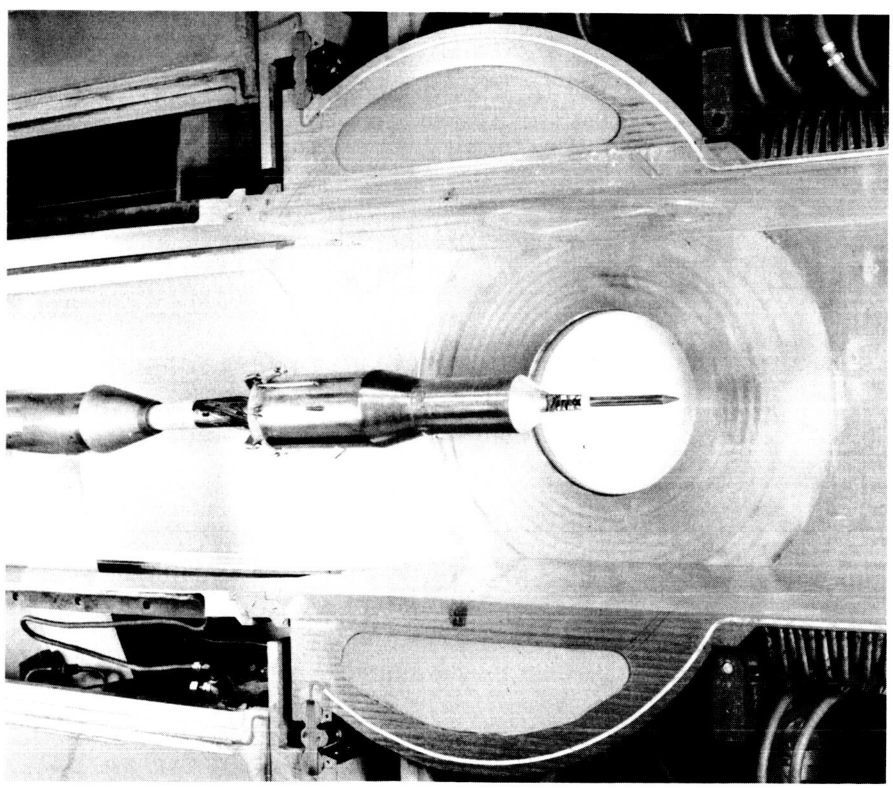


Fig. 31. ***Saturn*** model in the 21-inch HWT

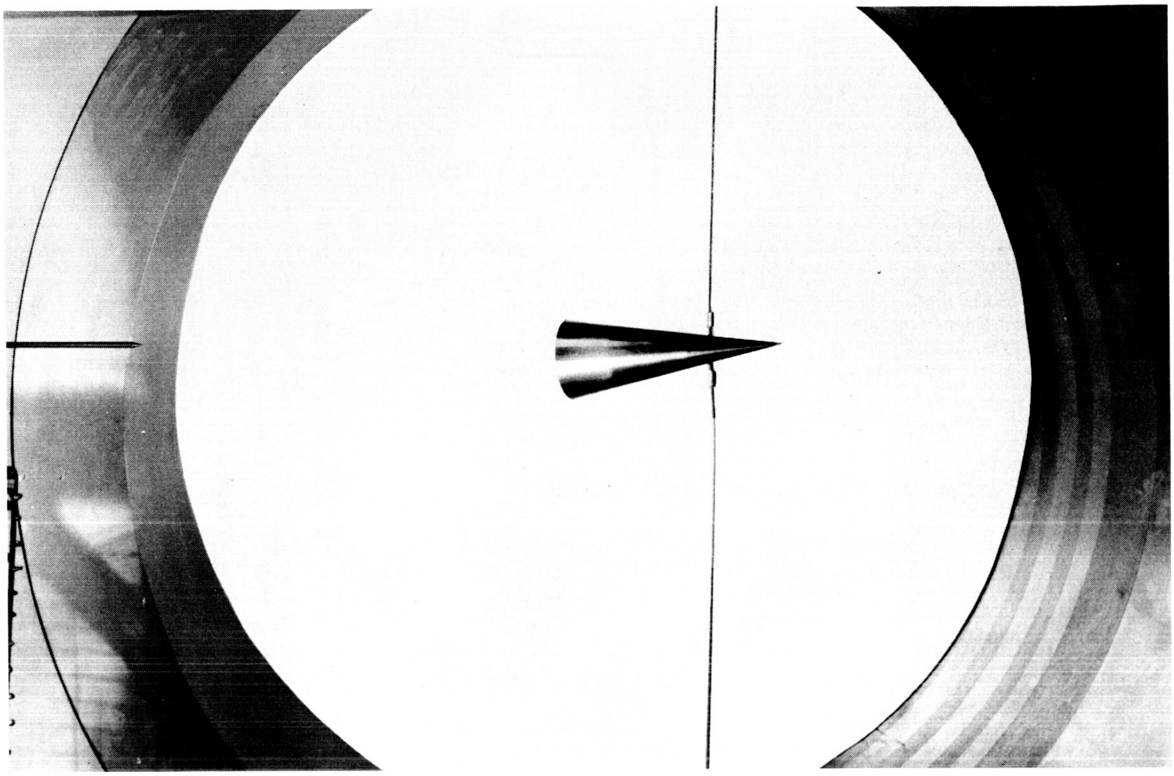


Fig. 32. Model supported on vertically oriented wire in the 21-inch HWT

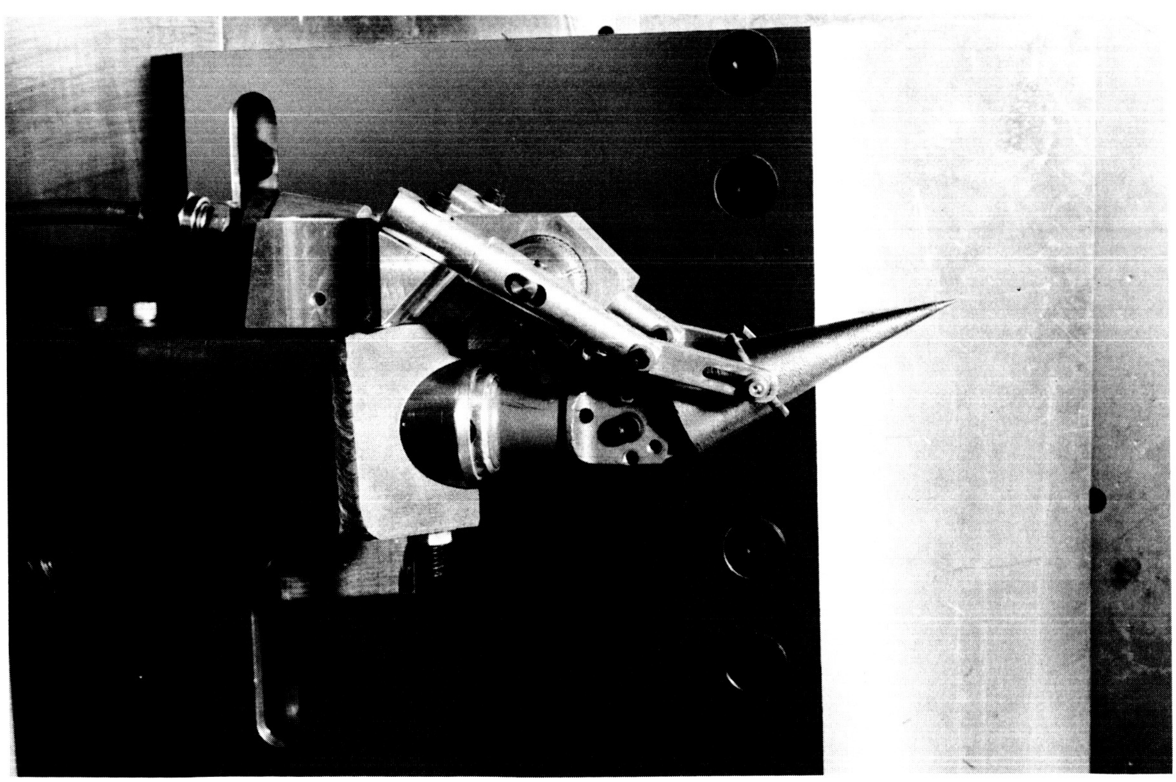


Fig. 33. Pointed 10-degree half-angle cone on pneumatic launch gun mounted in the 20-inch SWT